Energy absorption capabilities of recycled-plastic reinforcing bars for earthquake resistant housing construction

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Abstract

Mortar-free construction is considered efficient than confined masonry, because of more energy dissipation and better construction speed, in earthquake-prone regions. One of the main contributing elements is steel reinforcing bars, which provide stability through the vertical stiffeners in mortar-free construction. These bars are well-acknowledged for strength and toughness. However, these are costly and can lead to corrosion as well as such high strength is not required in small housing units. One solution is bamboo but due to its organic nature, its long term use is questionable. The housing construction industry is requiring cheaper and long termed materials as well. And the world is considering the sustainable recycling of plastic waste (with the least environmental concerns). This ideology gives a way to use recycled-plastic (RP) reinforcing bars for earthquake-resistant mortar-free construction of small housing units. In the current study, the waste plastic will be recycled and remolded using the extrusion method, to develop low-cost reinforcing bars. The extrusion method re-arranges the microstructure of the polymer and does not evolve harmful by-products. The bamboo will be taken as a reference. The tensile strength and toughness of both is assessed as per ASTM standards. RP bars are expected to become an alternative solution to steel or bamboo in mortar-free construction.

Keywords: Energy Absorption; Recycled-Plastic; Re-Bars; Earthquake Resistant Housing;

1 Introduction

Conventional masonry depends on the joints and the entire arrangement has a brittle behaviour. The main reason is that the basic building material involved is not capable to withstand the dynamic tensile loads imparted during the earthquake. The strengthening of masonry has been attempted previously, with variant mortar thickness and other possibilities to improve the interlocking having fibers with mortars. These construction strategies are for areas that do not have proper regulations for buildings and improvement in conventional construction might reduce the problems. These ideas conclusively improve the overall behaviour but still leave weak areas and cracks after failure (Buyukkaragoz & Kopraman, 2021). The arrangement does carry compressive loads up to a certain degree but explicitly does not cater to the seismic damage. Even with the best-controlled workmanship the joints somehow form a pattern of damage making it uncertain to repair areas for better energy absorption (Qamar et al., 2020). The mortar-free construction somehow devises a different concept to cater to this issue (Safiee et al., 2011). Leading the idea of Mortar free construction, it has also been assessed that the arrangement shows a good dynamic response. A study was conducted with fiber-reinforced concrete supported with coconut fiber ropes. Among other assessments, it was concluded that the tension generated during seismic loading was within the ropes tensile limits which made the arrangement worth exploration (Ali et al., 2013). Another extended study was conducted in which seismic loading of M_w 7.6 Kashmir, Pakistan 2005, M_w 7.0 El Centro, USA 1994 and M_w 8.3 Hokkaido, Japan 2003 was applied to mortar free block arrangement and it was seen that the uplift are not dependent upon peak ground acceleration, displacement, and frequency of the earthquake (Ali, 2018). These studies can be linked with the idea of another research that the ropes can counter the uplift (Ali, 2016). The idea of mortar-free construction needs more improvements with changes in other materials like blocks with lighter weight which further control the uplifts and allied behavioural loads in the mortar-free construction. The factor improving the response of the mortar-free construction is the vertical stiffener. In 2007, concrete stiffeners were used and the potential mortar-free masonry was found better than conventional construction (Thanoon et al., 2007). These stiffeners can be steel and can be coconut fibers as in previous studies but all are not as low cost as waste plastic. The Figure 1 shows a typical conventional masonry and conceptual mortar free masonry wall, the mortar free wall provides a substitutive efficient solution to conventional masonry.

(a)

(b)

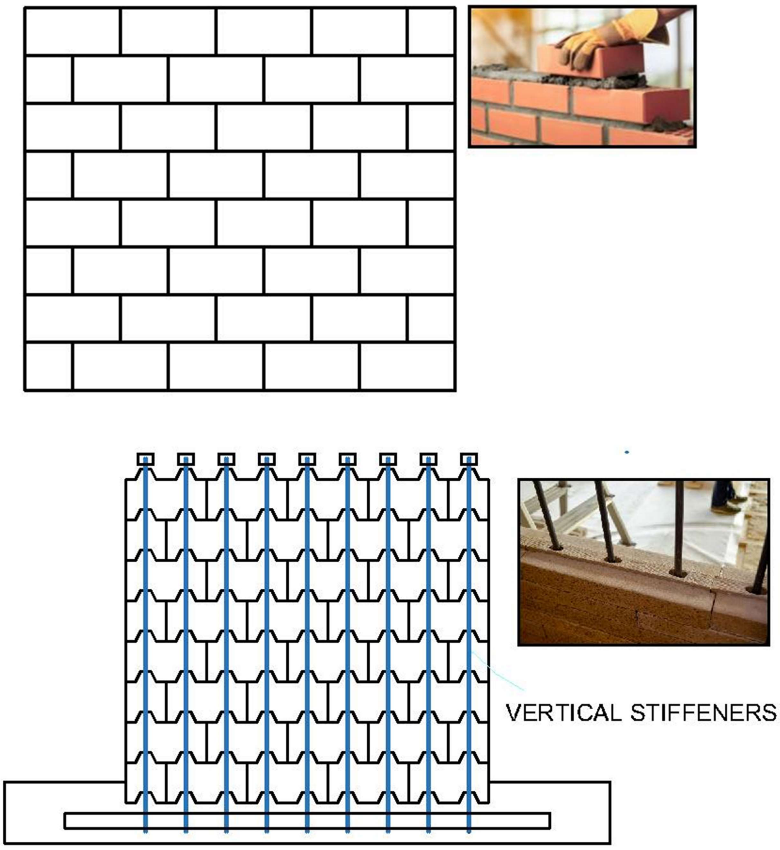

Figure 1. (a) Conventional Masonry Brickwork (b) Mortar free construction with vertical stiffeners

Fiber-reinforced polymer rebars are identified to replace steel reinforcement but the same is not so much popular in the commercial market. Steel reinforcement is expensive and gets corrosive under chloride attack (Adam et al., 2015). The FRP rebars are anisotropic and the behaviour along the direction of the fibers is better than in other directions. The dowel action is poor and they have no ductility (Mousavi & Esfahani, 2012). The FRP rebar in past research is proposed as a substitute for steel due to strength endurances, having lighter weight, and being a thermosetting plastic is prone to corrosion, it is also more friendly to the environment than steel and the expansion coefficient is close to concrete (Al-Khafaji et al., 2021). GFRP bars have also been used in another study with jute fibre and the possible spreading of fragments have also been controlled during impact loading (Ahmed & Ali, 2020). Studies (Patil & Manjunatha, 2020) discourage the conventional use of steel rebar (Emparanza et al., 2017). Bamboo has been used in different researches as a contented reinforcement material (Archila et al., 2018) and has been used to strengthen masonry and considerable improvements were recorded (Xu et al., 2019). In a similar trend bamboo has been used in beams which showed better tensile performance (Al-Fasih et al., 2021). The coir fibre rope reinforced beam were tested for dynamic response. The ductility and damping were recorded to increase (Ali & Chouw, 2008). This was also tested in columns and the results were exemplary in terms of dynamic responses especially before cracking (Ali, 2014).This ideology makes coir fibre rope another option instead of rebars. The material options are diverse and more sustainable variants are available to make rebars. In recent studies, waste plastic has been incorporated in the glass fiber rebars but only a small proportion of PET powder and PVC has been added which has made quite an improvement in the rebars (Jawad et al., 2019). This can be improvised and the manufacturing of the rebars can be explored with waste plastic recycling.

Plastic is entering the ecosystem adversely. The ecosystem due to the unmanageable waste is imparting an irreparable change. The disposal percentage to landfill sites and into the marine system is recorded 79% in 2015, and is increasing the toxicology in land and in freshwater. Stating these statistics, it was concluded in a research that this quantum of waste will increase alarmingly in 2050 with present disposal practices (Geyer et al., 2017). Different studies are depicting that plastic waste is becoming a menace and recycling is an appropriate solution. Different conversion methods are being explored for bulk utilization. The construction industry on the other hand can utilize this plastic waste to produce different construction items (Das & Ali, 2021). Table 1 shows different thermoplastic which can be used for plausible construction applications obtained from different sources (Li et al., 2020). After exploration, the material can be utilized by mechanical extrusion and secondary recycling methods can reutilize the plastic waste (da Silva & Wiebeck, 2020).

Table 1. Some Common Thermoplastic which can be used for plausible construction application.

Plastic	Property	Application
HPDE	Rigid and hard	Table, Chairs
LDPE	Flexible	Bricks and Blocks
PP	Hard and Flexible	Aggregates in Asphalt mix
PS	Brittle and Hard	Insulation
PET	Hard and Flexible	Fibre Cementitious composites
PC	Hard and Rigid	Roof and aggregates

Mortar-free construction is better than conventional construction. The system uses stiffeners and the materials available for use can be ropes, steel bars, or GFR bars, or concrete. Each of them has its pros and cons. In this study, the idea of mortar free construction system is proposed to be improved by the use of novel recycled waste plastic rebars. A set of rebars have been prepare with a shredded mix of waste plastic through the extrusion process. These rebars are compared with commercially available steel bars which are high in performance. In mortar-free construction, such high-end material might not be required and more economical and sustainable options are being attempted. The rebars produced shall provide tensile strength and can act efficiently as stiffeners. These are assessed for energy absorption and further exploration is required in a full-scale model of mortar-free construction to assess the behaviour of waste plastic rebars.

To the best of the author's knowledge, the recycled waste plastic rebars with 100% plastic waste have not been manufactured and energy absorption capabilities have not been assessed previously for intended use in mortar-free earthquake-resistant housing.

2 Experimental Procedures

2.1 Material – Novel Recycled Waste Plastic Rebars (RWPR) produced through Extrusion Process

The waste plastic was collected and shredded. No sorting was done and the mix contains High-density polyethylene (HPDE), Polyethylene (PE), and other plastic. The different form of plastics is usually very hard to separate until the proper origin is marked on the plastic or otherwise to be checked for composition though checks of composition. The plastic selected was unsorted as to cover bear minimum requirement of cost of the specimen. The mix of shredded material was put to the extrusion method and a temperature was kept between 150-170 ºC. A special steel dye was prepared to have longitudinal grooves 12 mm apart. Figure 2 (a) shows the typical arrangement of extrusion molding setup (b) shows the dye for preparation of Recycled Waste Plastic Rebars (RWPR) (c) shows the Novel recycled waste plastic rebars. The waste plastic enters the hopper and the gear system operated by a motor arrangement pushes the screw of the setup. The heaters are operated through a module showing indications through the thermocouple and the material that leave the machine semi-solid which after cooling hardens after 10-15 minutes depending upon the temperature of the machine. The rebars were marked before testing and were lightweight showing ductile physical properties.

2.2 Testing procedure

No standards exist for the testing of novel recycled waste plastic rebar. The test setup available contains a servo-hydraulic universal testing machine as shown in Figure 3. The A615 ASTM procedure was used to test for tensile strength. The weights of the samples were taken and the total length of the samples was between 0.6 m to 0.87 m. The steel rebars were taken as reference and No.6 bar having diameter of 6.98 mm and 6.62 mm. A sample of bamboo was also tested to check the tensile strength absorption. The Recycled Plastic rebars were easy to bend and therefore, a bend test was not required. The diameter and other perimeters of the bars is shown in Table 2. After testing the results were deduced to calculate the area under the stress Vs strain curve. The overall elongation was also

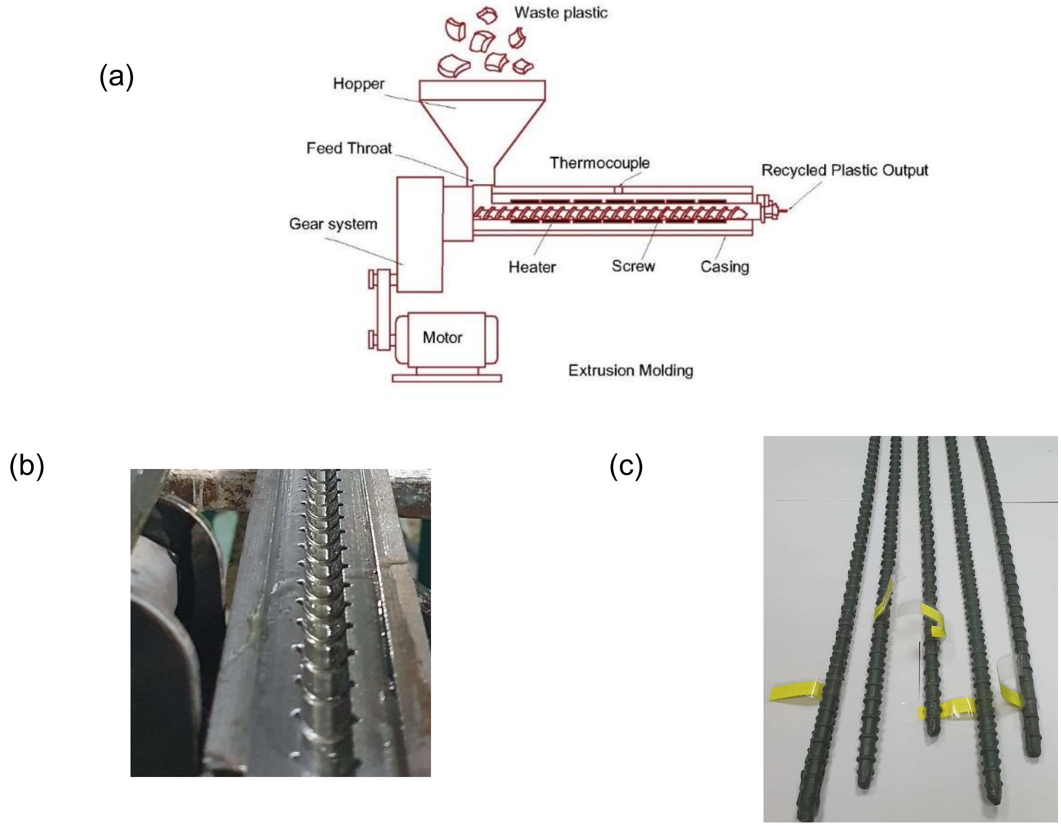

Figure 2. (a) Extrusion process for the production of waste plastic rebars (b) Dye for preparation of WP rebars (c) Novel waste plastic rebars

(a) (b) (c)

Figure 3. Test Setup for Tensile Energy Absorption(a) Recycled waste plastic (b) Bamboo (c) Failure of recycled waste plastic rebars

3 Results and Analysis

3.1 Tensile behaviour

The tensile stress – strain behaviour is shown in Figure 4. The initial application of load shows a rise as an elastic behaviour for both the bamboo as well as recycled waste plastic rebars. The maximum values for the tensile stresses is 14.60 and 30.24 MPa for RP and bamboo respectively. The corresponding values at this maximum strength are presented in Table 2. The bamboo shows initial breakage at this peak load and then loses its strength and then second stage peak load is also observed. This is successive ruptures occurred during testing for bamboo. Due to the fibrous nature of the bamboo the failure is shown in the down slope which is not able to carry more load. The slope for recycled waste plastic bar is smoother and shows that elongation does not have successive ruptures. Before the final rupture the final curve again shows a flexible breakage. The values for tension and energy absorption are deduced from the test are tabulated in table 2.

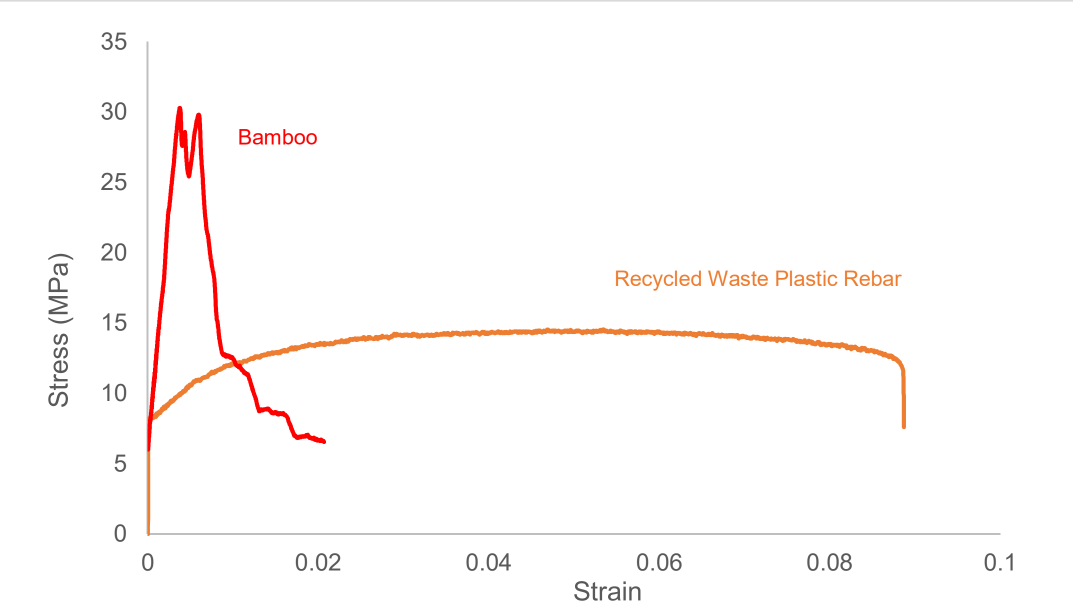

Figure 4. Stress-Strain comparison of recycled waste plastic and bamboo

3.2 Energy absorption capabilities of recycled waste plastic rebars

The Energy absorption capability shows that before failure the material has sufficient ability to absorb energy and in an earthquake-prone region the recycled waste plastic rebar shall be an economical solution. The maximum tensile load for bamboo is observed to be 4.64 KN and for RP bars is 1.69 KN. The values obtained by for total energy absorption is the area under the curve of the stress strain diagram which comes from calculation to be 1053.10-1192.97 KJ/m^3. This energy absorption is less for bamboo about 295.24 KJ/m^3 due to the reason that after failure the material could not sustain more stresses. The toughness index computed by dividing the total area under the curve with the area under the curve prior to yield in RP bars and first rupture for bamboo. The values of toughness index are 10.48 for RP and 4.13 for bamboo. The values of energy absorption are almost four times and the toughness index is more than double. The RP can be further improved if the process of manufacturing recycled waste plastic is further explored with additives.

Table 2. Test results.

Rebars	Weight per unit length (Kg/m)	Diameter (mm)	Nominal Area (mm^2)	Max Tensile Load (KN)	Yield Stress (MPa)	Max Strength (MPa)	Tensile Energy Absorption (KJ/m^3)	Toughness Index (E/E$_t$)
WP* No. 13	0.10	12.10	115.00	1.68	7.60	14.60	1192.97	10.48
Bamboo	0.12	13.97	153.34	4.64	30.24	30.24	295.24	4.13

* Waste Plastic

4 Recycled Plastic Rebars for Mortar free construction

The phenomenon shown by recycled waste plastic rebars is different than that of steel or other variant material available for rebars. The strength is very less than that of steel primarily because the waste plastic was not sorted and the material is lesser in density than steel. As in previous studies already discussed the mortar-free construction imparts tension in the stiffeners due to uplift. These recycled waste plastic re-bars have shown some strength and this strength is considerable if we consider the testing of coconut fiber ropes in mortar-free construction done in previous studies (Ali, 2018). The ropes were of three times more thickness of about 36 mm and the values of tensile strength are comparable. It is plausible that waste plastic rebars shall also prevent collapse when used in mortar-free construction. The added benefits are that it will reduce the plastic menace and reduce the cost of construction manifold. Unlike steel, it will also not corrode and the problem of ductility of GFRP rebars is also catered. The mortar-free construction proposed in previous researches also explicitly explains that the keys of the blocks are arranged in such a way that during a seismic activity the block should reassemble with its self-weight. This mechanism shifts a lesser amount of energy to the stiffeners and the required energy absorption prevents the failure of the mortar-free system. The RWPR can be improved if the polymeric chain is improved by additives in the extrusion process.

5 Conclusion

Recycled waste plastic as a material has its own set of qualities and have considerable toughness and energy absorption. Other bars available in the market have issues like steel is very expensive and is prone to corrosion, the GFRP are not ductile, other organic bars like bamboo and ropes are not long lasting. Following conclusions can be drawn

i. The intended use to recycle waste plastic to produce rebars is a plausible and sustainable option for the low-cost construction industry. This can reduce the construction cost and reduce the quantum of plastic pollution.

ii. The tensile behaviour is smoother and elastic. The RP bars show ductility in the load deformation relationship.

iii. The recorded values of waste plastic rebars show less maximum tensile loads than bamboo. The values of energy absorption and toughness index is considerably greater for RWPR than bamboo.

iv. The uplift forces during a seismic activity for mortar-free construction are also dependent on the shape of the blocks and the mechanism which is imparted. The capability required by stiffener to control the uplift that is caused due to the earthquake forces is meagre. Therefore, the use of steel or GFRP has comparatively high strength is a waste in terms of economy, strength.

The waste plastic properties can be improved by the use of additives and sorting. The variants of the recycled waste plastic rebars can be put to test with a real mortar-free setup over a shake table to actualize the efficiency of stiffeners in the system. The exploration of residual strain/displacement of waste plastic rebars, is required in future studies, through reverse-cyclic stress strain graph. This can broaden the intended use of waste plastic rebars in earthquake engineering applications.

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