Construction and Building Materials 198 (2019) 629–637

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Application of modified carpet waste cuttings for production of eco-efficient lightweight concrete

Hossein Fashandi [a,*], Hamid Reza Pakravan [b,*], Masoud Latifi [b]

[a] Department of Textile Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Textile Engineering, Amirkabir University of Technology, Hafez Avenue, Tehran 15914, Iran

HIGHLIGHTS

- Introducing new type of fibrous based lightweight aggregate.
- Modified carpet waste with density lower than 500 kg/m^3.
- Alternative usage for carpet waste materials.
- Lightweight concrete with improved ductility and energy absorption properties.

ARTICLE INFO

Article history:
Received 15 November 2017
Received in revised form 21 November 2018
Accepted 21 November 2018

Keywords:
Carpet waste
Modified waste
Lightweight aggregate
Concrete
Mechanical properties

ABSTRACT

In the present work the carpet waste is modified to produce a new type of lightweight aggregates with a low bulk density for applications in concrete materials. The study suggests a new application for this kind of synthetic fiber-based floor covering materials to reduce the rate of disposal and protect environment through its contribution in cleaner environment and production. In this respect, physical and mechanical properties of lightweight concrete made from modified needle-felt carpet waste cuttings are investigated. A series of experiments including density measurement, compression, flexural and water absorption tests are performed to study the performance of concrete composed of carpet wastes. Through the investigation, the carpet wastes exhibited remarkable potential to be considered as lightweight aggregates. This type of materials increased ductility and load-bearing capacity of concrete in post-cracking region in a manner analogous to virgin synthetic fibers. The results of the study also emphasize the high environmental potential of modified carpet waste cuttings for the production of sustainable lightweight concrete and a replacement for usage of virgin polymer fibers.

1. Introduction

Carpets are the most popular floor covering materials compared to other flooring materials. Carpets and area rugs accounted for 51.2 percent share in square feet of the U.S. floor covering market in 2017 [1]. This type of products uses a high volume of virgin fibers as opposed to reclaimed or recycled fibers. Currently, in united states alone, it is estimated that the usage of new fibers for face yarn in carpet industry will rise to 1.2 milion tons by 2020 [2]. Annually a large volume of post-consumer carpets are replaced by new products and dumped into the landfills [3]. The rate of carpet disposal is about 4–6 million tons per year worldwide [4]. Additionally, carpet wastes are also produced during the manufacturing process such as trimming the edges of carpet and producing sheared face yarns [5].

Due to the environmental impacts of wastes, the legal frameworks for treating waste have been established around the world. According to Directive 2008/98/EC, the European countries should recycle 50 percent of household waste by 2020 [6]. The ways towards sustainable Europe's economy by 2050 are described by the roadmap to Resource Efficient Europe (COM(2011) 571) according which resource productivity must be increased and economic growth have to be decoupled from resource use and its environmental impacts [7].

With the growth of economy, the need for raw materials is steadily increasing. The linear economy of "take-make-use-dispose" is not a sustainable model and it is now failing. Therefore, the circular economy aimed at limiting the extraction of raw materials and the production of waste has been introduced. According to a Zero Waste Program for Europe, in systems based on circular economy,

* Corresponding authors.
E-mail addresses: h.fashandi@cc.iut.ac.ir (H. Fashandi), pakravan@aut.ac.ir (H.R. Pakravan).

https://doi.org/10.1016/j.conbuildmat.2018.11.163
0950-0618/

the added value in products is preserved and waste is eliminated [8].

Although there is already an increased attention towards recycling carpet waste and their use as post-products applications, most carpet wastes continue to be disposed in landfills [9]. Therefore, innovative alternatives for utilization of the post-consumer carpets have become an emerging need [10]. The disposal of fibrous wastes is a major problem for environment due to non-degradable characteristic of this kind of materials in landfills for a very long period of time. This is not only a cause for environmental concern, but also represents a waste of advantageous resources [11]. In this respect, million dollars are lost per annum as a result of carpet waste landfilling [12].

With a broad spectrum of applications, polymeric materials such as textiles and fibrous materials contribute to increased volume in the solid waste stream. Also due to the scarcity of landfilling space and its high cost of developing and managing, waste reuse has been introduced as a promising alternative to disposal [13]. Furthermore, burning of fibrous material wastes releases highly toxic fumes in the surrounding air which puts human health in danger [14].

Carpets are an enriched source of fibers attached on the surface of carpet. After an appropriate treatment, the carpet wastes can be used for manufacturing of beneficial products such as a potential fuel substitute in cement kilns, mass production as filler, sound insulating mats, flower pots or fencing posts [4,15]. Using mechanical methods, the face yarns of post-consumer carpets can be recycled into short fibers for applications such as reinforcing materials and filler [5]. Researchers have reported that polymeric fibers' waste have a great potential to be used as filler in the different construction materials such as concrete, asphalt, soil, etc. [16] and [17]. The recycled fibers are generally of lower cost than virgin fibers and using these materials eliminates the need for waste disposal in landfills [18].

Mohammadhosseini and Awal [19] have investigated the effect of face fibers of post-consumer carpet on the physical and mechanical performance of concrete. They stated that using these waste fibers as reinforcement in concrete is an effective way to reduce the disposal of waste and at the same time decreases the amount of virgin fibers used in cement based materials. Mirzababaei et al. [10] reported the effectiveness of carpet waste fibers for reinforcement of clay soils. They used two different types of waste fibers recovered from carpet manufacturing processes, *i.e.* shearing and edge-trimming processes. Increasing the fiber content of both fiber types significantly increased unconfined compressive strength of clay soil reinforced with waste fibers. Ucar and Wang [20] have used recycled fibers from a post-consumer carpet as reinforcement in developing lightweight concretes. They reported that incorporation of recycled post-consumer carpet waste fibers into concrete mixture produces a lightweight and tough cement boards.

Aghaee and Foroughi [21] have used textile waste for producing lightweight concrete. In a study, Wang et al. [22] investigated the pull-out behavior of carpet face yarn and backing yarn from mortar matrix. Schmidt and Cieslak [23] determined the adhesion between recyclate components of carpet such as polypropylene pile fiber and coating particles with concrete. They reported that there is a strong adhesion between pile fibers and concrete which is even higher than adhesion between sand and concrete.

Needle-felt carpets (or Needle-punched carpets) are a thin and dense type of floor covering materials for rough use which account for 9% of the carpet market [24]. Schematic descriptions of the needle-felt and tufted carpets are shown in Fig. 1. The conventional uses of needle-felt carpet include in indoor-outdoor carpeting with heavily used areas, residential areas and making automotive carpet, commercial facilities or even some carpet tiles.

In this kind of carpet, matted layer of short fibers is intermingled and entangled with the aid of barbed needles penetrating through the fibrous assembly. Additional needling makes the final structure and design of the products. Furthermore, the subsequent resin treatment (so-called mineral filled latex) is regarded for coating the underlay layer and fixing the fibers. Needle-felt carpet is reasonably more durable and cheaper in comparison to tufted carpet. Contrary to the tufted carpets, it is not possible to easily recycle and extract fibers from the surface of needle-felt carpet wastes when backing resin is used. Commonly, the carpet waste containing the latex has not found suitable uses while it contains the major part of the waste going into the landfills [4].

An alternative for reuse of resin backed carpet waste is shredding it into small pieces for filler applications in other industries. Rushforth et al. [25] have investigated the combination of granulated backing and recovered pile surface of carpet tiles using SBR (styrene butadiene rubber) binder for production of underlay material with impact sound insulation properties. The impact sound insulation of the sample produced from carpet waste exhibited comparable performance to commercial products.

The needle-felt carpet due to the tight fiber fixation cannot be recycled or directly reused in the textile processing. Therefore, emerging plans are needed to manage the post-consumer needle-felt carpets in order to reduce landfilling of this kind of wastes. The needle-felt carpet cuttings are very light in weight which can be considered as lightweight aggregate for concrete materials after

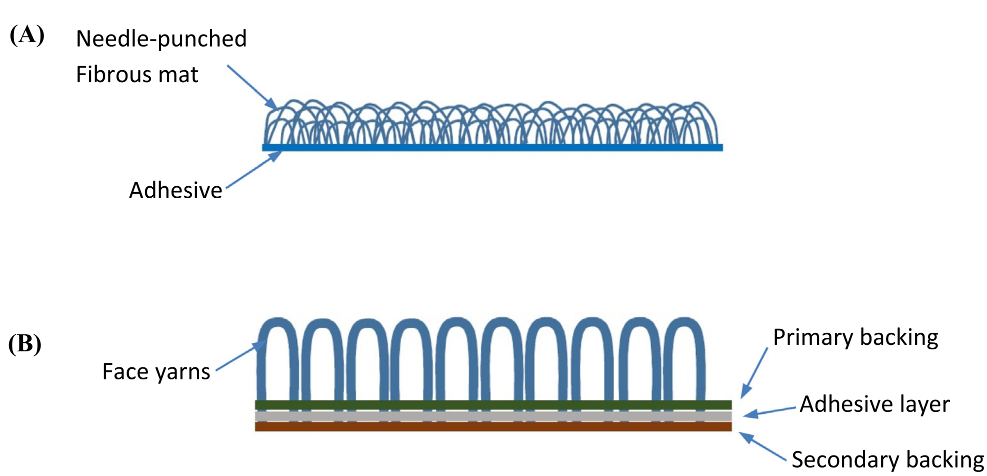

Fig. 1. Schematic description of: (A) Needle-felt carpet, (B) Closed loop tufted carpet.

employing appropriate treatment. In this respect, the present study investigates the effect of the needle-felt carpet waste cuttings as lightweight aggregate on concrete performance through an experimental testing program. Therefore, this study aims to explore usefulness of this kind of waste materials as a new construction material.

2. Experimental program

2.1. Characterization of materials

Carpet waste- In this research a needle-felt carpet waste with PP fiber mat and SBR latex binder backing layer from a carpet-manufacturing mill was used. The needle-felt carpet is a nonwoven fibrous mass layer densified and bonded together with the mechanism of needling. Fig. 2 shows cross-sectional images of carpet waste before and after latex impregnation. Commonly, needle-felt carpet has one side backing layer with latex binder (Fig. 2A). For the increasing dimension stability of waste cuttings additional latex impregnation was also applied to the upper surface of carpet as illustrated in Fig. 2B. It is clearly obvious from the figure that a fibrous structure is embedded between the two hard layers of binder mixture. The binder used for surface coating of carpet waste was a mixture of SBR latex with $CaCO_3$. After curing of surface coating, the carpet waste was cut into small pieces with maximum dimensions up to 4 mm × 4 mm, as shown in Fig. 3.

Matrix- Portland cement type II from Tehran cement Co. was used in this study. The nominal maximum aggregate size of sand was 4.75 mm. The silica-fume (SF) was used as supplementary cementitious material in this study.

Mix proportions- Mix proportions used for production of concrete are given in Table 1. Carpet wastes as aggregate replacements were added in three weight fractions, *i.e.* 1.0, 2.0 and 3.0 wt% with respect to the weight of sand. Because of high volume to weight ratio of this type of waste materials, a small amount of waste content is used in this study. Water to cement ratio for all formulations was selected to be 0.43. Silica-fume was used by 10% of cement weight content.

Specimen preparation- For production of concrete, solid ingredients including cement, silica-fume and aggregates were dry mixed using a mortar mixer for approximately 2 min. Then water was gradually added and mixed for about 3 min until a uniform mixture was obtained. Once enough workability and viscosity was demonstrated by mortar mixer, for uniform distribution of waste particles, the carpet wastes were added slowly to the concrete and additionally mixed for 5 min. The fresh concrete was then transferred into steel molds and compacted for 1 min using a vibrating table. The specimens were then stored at room temperature for 24 h before demolding. The prepared specimens were kept in water tank for 28 days before testing.

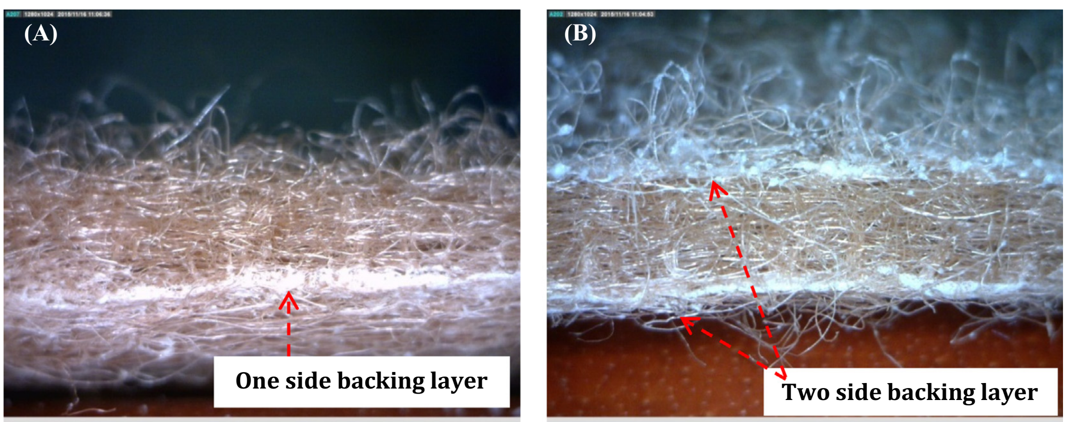

Fig. 2. Cross-sectional image of carpet waste: A) original form with one side backing layer, B) additional latex treatment (two side backing layer).

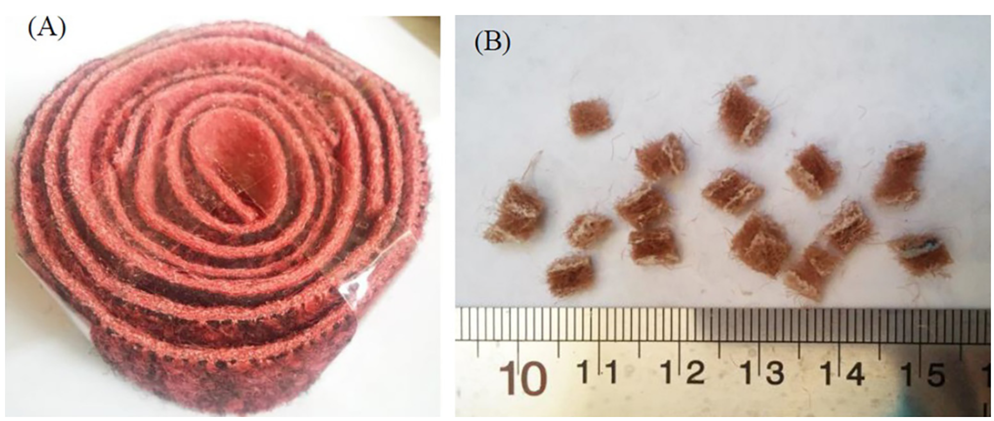

Fig. 3. Carpet waste: A) original form, trimmed edges, B) Carpet waste pieces.

Table 1
Mix proportion of the prepared concrete mixtures.

Mix. name	Cement (kg/m^3)	Aggregate (kg/m^3)	Silica fume (kg/m^3)	Water* (kg/m^3)	Carpet waste (kg/m^3)	Carpet waste** (wt.%)
Control	550	1410	55	260	0	0
1% waste	550	1396	55	260	14	1.0
2% waste	550	1382	55	260	28	2.0
3% waste	550	1368	55	260	42	3.0

* Water to cement ratio of 0.43.
** Weight ratio of aggregate.

2.2. Testing

Tensile and bending tests were used to evaluate the effect of surface coating on mechanical properties of needle-felt carpet waste. The tensile test was carried out using a universal tensile machine with a span length of 100 mm. The span length for evaluation of bendability of carpet waste was adjusted to 50 mm.

The density of hardened concrete, ρ (Kg/m^3), was calculated by immersion method as described by Eq. (1):

$$\rho = \frac{W_{Air}}{V_w} \quad (1)$$

where, W_{Air} (kg) is the weight of sample in air and V_w (m^3) is the volume of sample determined from immersion in water.

Water absorption (W_A) was determined according to the ASTM C642 standard. The samples were firstly dried in an oven at 100 ± 5 °C to reach a constant weight (W_d) and then the samples were fully immersed in water for 72 h. After that, the weight of the saturated surface-dried sample (W_w) was determined and the percentage of increase in the weight was recorded as the water absorption (Eq. (2))

$$W_A(\%) = \left(\frac{W_w - W_d}{W_d}\right) \times 100 \quad (2)$$

Flexural test was performed on prisms specimens with dimensions of 160 × 40 × 40 mm^3 using three-point bending test method. A uniaxial load was monotonically applied to the prisms at a rate of 1 mm/min with a span length of 120 mm. During the flexural tests, load and mid-span deflection were recorded.

Cubic specimens (40 × 40 × 40 mm^3) cut from fractured samples under flexural load were used for determination of compressive strength according to the ASTM C39 standard. At least three specimens were tested for each formulation to determine the average compressive and flexural strength. For each sample, the value averaged over all measurements was reported.

3. Results and discussion

3.1. Influence of surface coating for carpet waste

Mechanical properties of carpet waste before and after surface coating are evaluated using tensile and bending test. Tensile behavior of carpet waste before and after surface coating (as described in Section 2) is shown in Fig. 4A. As shown, both tensile strength and elongation at break of carpet waste after surface coating have been increased. The increment percentages of tensile strength and elongation at break were calculated to be 38% and 15%, respectively, compared to un-coated waste.

The bending test was also considered to evaluate the deformability of carpet waste after surface coating; the graphs have been shown in Fig. 4B. According to the load-mid span deflection curve, rigidity of carpet waste after latex coating has been increased by more than approximately 5 times. This result proves the great contribution of surface coating to improve the dimensional stability of the prepared carpet wastes. This dimensional stability facilitates cutting the carpet wastes as potential aggregate for application in concrete materials. Table 2 presents the physical and mechanical properties of carpet waste cuttings after surface coating.

Table 2
Physical and mechanical properties of carpet waste cuttings after surface coating.

Properties	
Dimension (mm^2)	4 × 4
Water absorption (%)	83.02
Bulk density (kg/m^3)	≈300
Tensile strength (MPa)	4.95
Compressive strength	poor

Table 3
Properties of hardened concrete sample.

Mix. name	Density (Kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)
Control	2274 ± 17	31.70 ± 0.95	6.21 ± 0.36
1% waste	2180 ± 24	29.99 ± 0.54	6.14 ± 0.23
2% waste	2119 ± 23	29.01 ± 1.68	5.87 ± 0.14
3% waste	1955 ± 26	27.22 ± 0.95	5.72 ± 0.19

3.2. Density of concrete

Density of concretes containing different contents of carpet wastes has been tabulated in Table 3. It is observed that incorporation of carpet waste even at lower content has resulted in reduction in density of concrete. According to the results, addition of 1%, 2% and 3% of carpet waste has decreased the density of concrete by 4.1%, 6.81% and 14.02%, respectively. It can be concluded that despite the very low content of carpet waste, its effect on density reduction of concrete is remarkable. This is due to the low density and bulky property of this waste material. Approximately, the density of carpet waste is lower than that of sand by 80–90%. It indicates that carpet waste has a great potential to be employed as lightweight aggregate for concrete.

In Table 4, the positive contribution of carpet waste to concrete density reduction investigated in this study has been compared with results associated with different polymer-based waste particles reported in earlier studies. As indicated in Table 4, the waste contents considered in previous studies are significantly larger than those investigated in the present study. This is while the carpet waste particles exhibit superior performance over other types of waste particles. Strictly speaking, a small amount of carpet

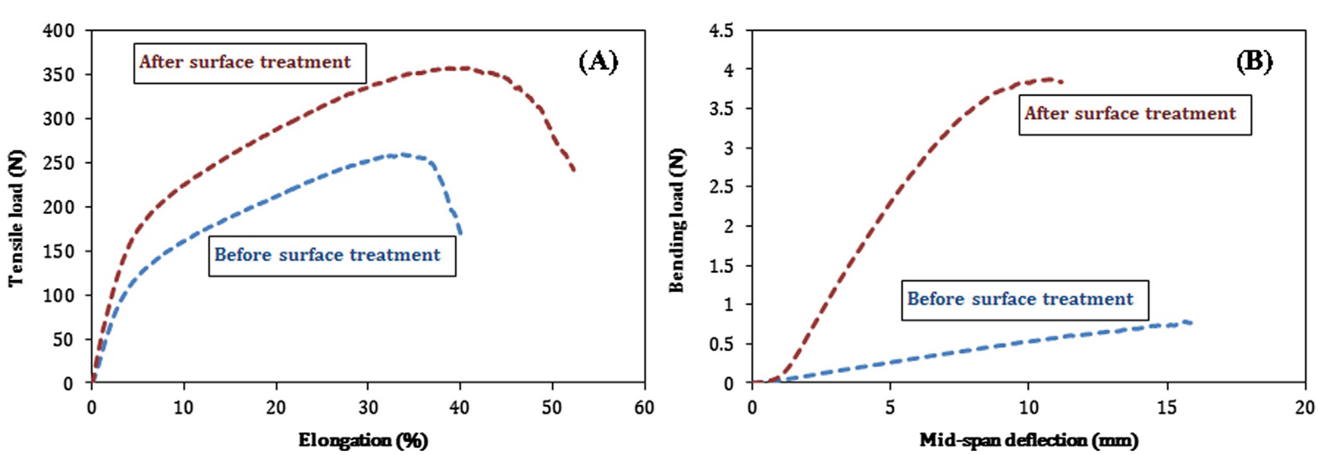

Fig. 4. Tensile and deformability behavior of carpet waste before and after surface coating.

Table 4
Effect of different types of polymer-based recycled waste materials on density of concrete.

Ref.	Waste type	Waste content (%)	Density (kg/m^3)	Reduction in density over control sample (%)
This study	Carpet waste	0	2274	0
		1.0	2180	−4.1
		2.0	2119	−6.81
		3.0	1955	−14.02
Luis Ruiz-Herrero et al., 2016 [26]	Waste PVC particles	0	2399	0
		2.5	2382	−0.70
		5.0	2344	−2.29
		20	2018	−15.88
Ismail and Al-Hashmi, 2008 [27]	Waste plastics (mainly PE and PS)	0	2403	0
		10	2311	−3.82
		15	2246	−6.53
		20	2225	−7.40
Kou et al., 2009 [28]	PVC granules obtained from scraped PVC pipes	0	1750	0
		5	1730	−1.14
		15	1620	−7.42
		30	1600	−8.57
Rahmani et al., 2013 [29]	Waste PET particles	0	2281	0
		5	2258	−1.01
		10	2238	−1.88
		15	2209	−3.16

waste particles leads to considerable reduction in density of concrete compared to other polymer-based waste particles.

3.3. Compressive strength of concrete

Compressive strength of concretes containing different contents of carpet wastes has been given in Table 3. As evident, the compressive strength is reduced by increasing the content of carpet waste. Incorporation of carpet waste with weight fraction of 1.0%, 2.0% and 3.0% results in reduction in compressive strength of concrete by 5.39%, 8.48% and 14.13%, respectively. However, irrespective of carpet waste content, the compressive strength of all prepared samples is still higher than the minimum compressive strength requirement for a structural concrete, *i.e.* 17.24 MPa for 28 days cured sample [27]. Fig. 5 shows the relationship between dry densities and corresponding compressive strengths of the prepared concrete samples with different contents of carpet waste. As evidenced by Fig. 4, the compressive strength of the concrete samples linearly decreases by decrease in the sample dry density. A linear relationship with R-square of 0.980 can be established to correlate the dry density and the compressive strength as presented in Fig. 5.

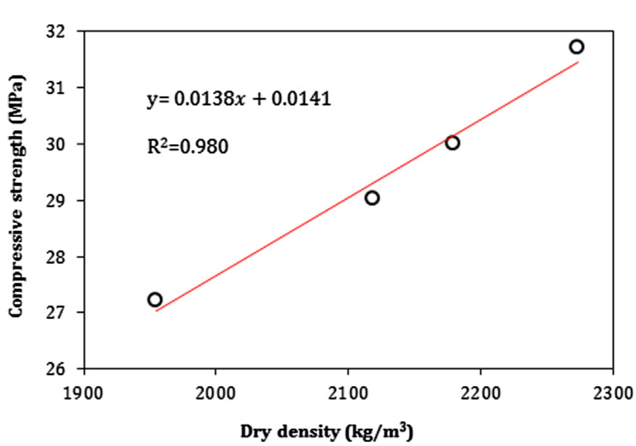

Fig. 5. Relationship between the dry density and the compressive strength of prepared concrete samples.

Although incorporation of carpet waste decreases the compressive strength, but in comparison with control sample, the lightweight concrete does not display brittle fracture behavior under compressive test due to its higher energy absorption capacity. The carpet wastes prevent the prepared concrete samples form sudden collapse due to bridging ability of their fibrous structure.

In Table 5 the performance of different waste types including carpet waste investigated in the present contribution and other polymer-based wastes from recently published works, has been compared. As shown in Table 5, regardless of waste type, the compressive strength of concrete samples is a descending function of waste content. Additionally, one can vividly confirm that the carpet waste has no superiority over other polymer-based waste materials. This lies in the fact that carpet wastes are weak in compression compared to plastic waste particles and incorporating a low content of carpet waste yields significant reduction in concrete compressive strength.

3.4. Flexural behavior of lightweight concrete

Flexural behavior of the prepared concretes containing different weight fractions of carpet waste cuttings using load–deflection curves are shown in Fig. 6. As shown, control concrete without carpet waste cuttings exhibits brittle behavior with a deflection capacity below 0.5 mm. According to the load-deflection curves it is indicated that the post-peak behavior of the prepared concretes is strongly influenced by increment in the waste content. It is obvious that the brittle concrete has been transformed into a ductile one as a direct consequence of incorporation of carpet waste. It can be interpreted by the bridging ability of carpet waste in resisting against opening of emerged cracks. Since this type of wastes has fibrous structure, they can effectively bridge the cracks emerged around them and avoid sudden decline of flexural load. By increment the content of carpet waste the probability of finding more wastes around the cracks increases. For the sake of more clarity, a comparison between load-deflection curves of the concrete samples to deflections of 0.5 mm and 2 mm is presented in Fig. 7. As seen from Fig. 7, by increment in the carpet waste, reduction of load after first-peak is reduced.

In Fig. 8A the stress at maximum load (flexural strength), deflection up to 0.5 mm and 1.0 mm of the concrete samples with different contents of carpet waste cuttings have been compared.

Table 5
Comparison between compressive strength of concrete with different types of waste materials.

Ref.	Waste type	Waste content (%)	Compressive strength (MPa)	Reduction in compressive strength over control sample (%)
This study	Carpet waste	0	31.70	0
		1.0	29.99	−5.39
		2.0	29.01	−8.48
		3.0	27.22	−14.13
Luis Ruiz-Herrero et al., 2016 [26]	Waste PVC particles	0	34.6	0
		2.5	31.9	−7.80
		5.0	23.3	−32.65
		20	6.6	−80.92
Ismail and Al-Hashmi, 2008 [27]	Waste plastics (mainly PE and PS)	0	44.23	0
		10	33.39	−24.50
		15	29.72	−32.80
		20	29.72	−32.80
Kou et al., 2009 [28]	PVC granules obtained from scraped PVC pipes	0	40.8	0
		5	37.1	−9.06
		15	33.2	−18.62
		30	31.9	−21.81

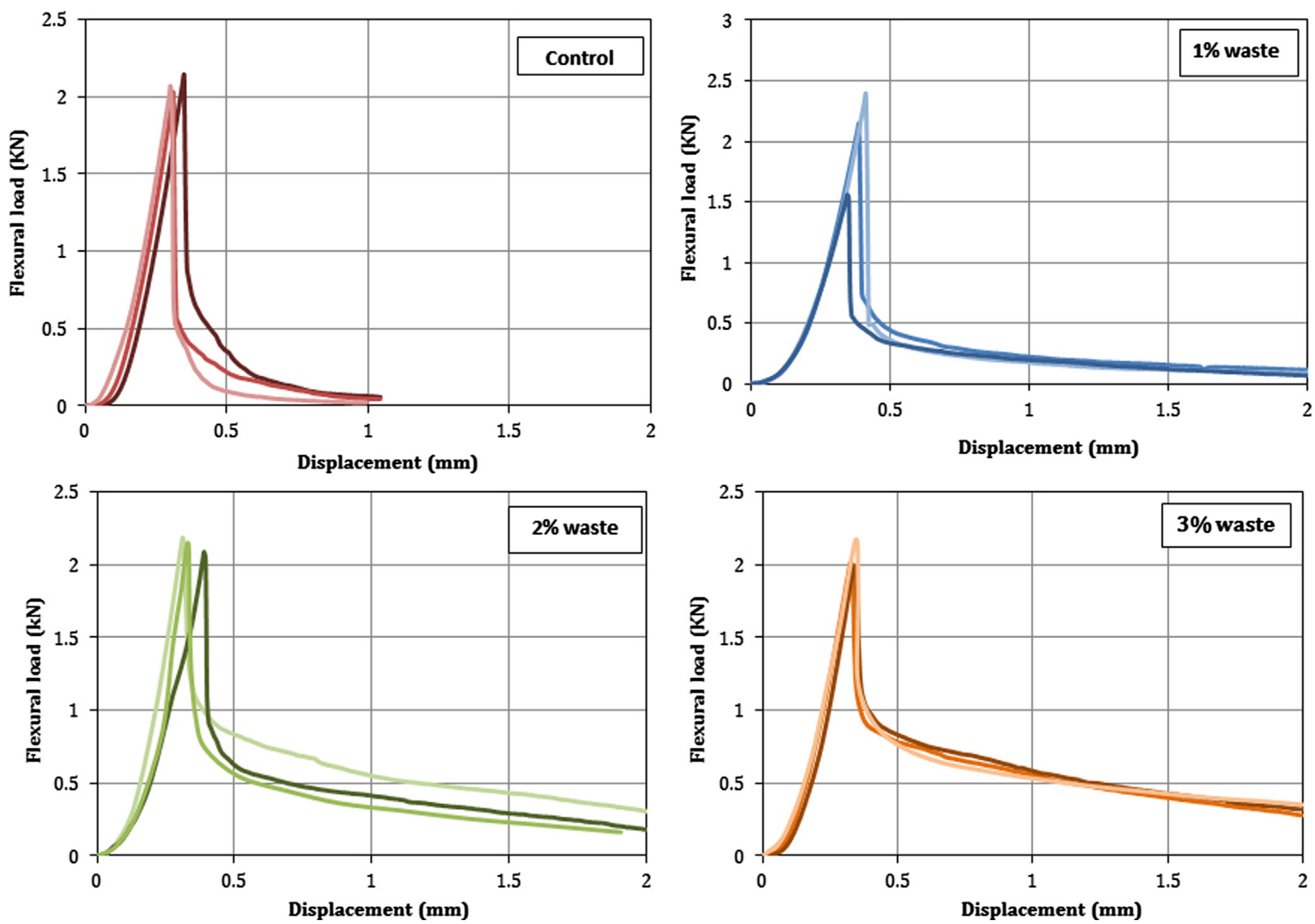

Fig. 6. Flexural load-deflection curves of the prepared concretes with different waste contents to deflection of 2.0 mm.

Obviously, incorporation of the carpet waste into mixture results in decreasing the flexural strength of the concrete. According to Fig. 8B, addition of carpet waste cuttings by 1.0, 2.0 and 3.0 wt% has decreased the flexural strength of the prepared concretes by 1.13%, 5.48% and 7.89%, respectively. Although the bulk density of the carpet waste cuttings is very low, *i.e.* around 300 kg/m^3, but its negative effect on the flexural strength of concrete is not as very high as other type of lightweight aggregates.

Incorporation of carpet waste cuttings in concrete has demonstrated significant influence on post-cracking strength. As indicated in Fig. 8A, increment in the carpet waste content has steadily increased post-cracking stress at deflection of 0.5 mm and 1.0 mm. The percentage enhancement of the post-peak load for the concrete containing carpet waste, *i.e.* at 0.5 mm deflection, is as high as 200% in comparison to control sample.

In Fig. 9 flexural toughness indices I5 and I10 of the concrete samples determined according to the ASTM C1018 have been shown. The flexural toughness indices are calculated through the deflection in post-peak region in relation to the first-crack deflection, δ_p, as following:

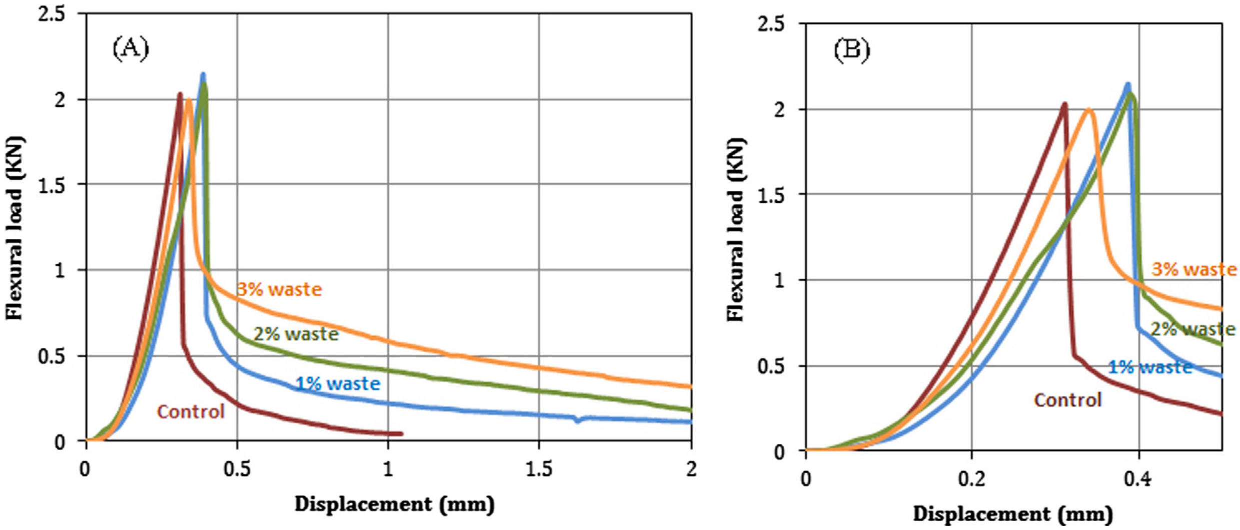

Fig. 7. Comparison between load-deflection curves of the prepared concretes to deflection of: A) 2 mm, and B) 0.5 mm.

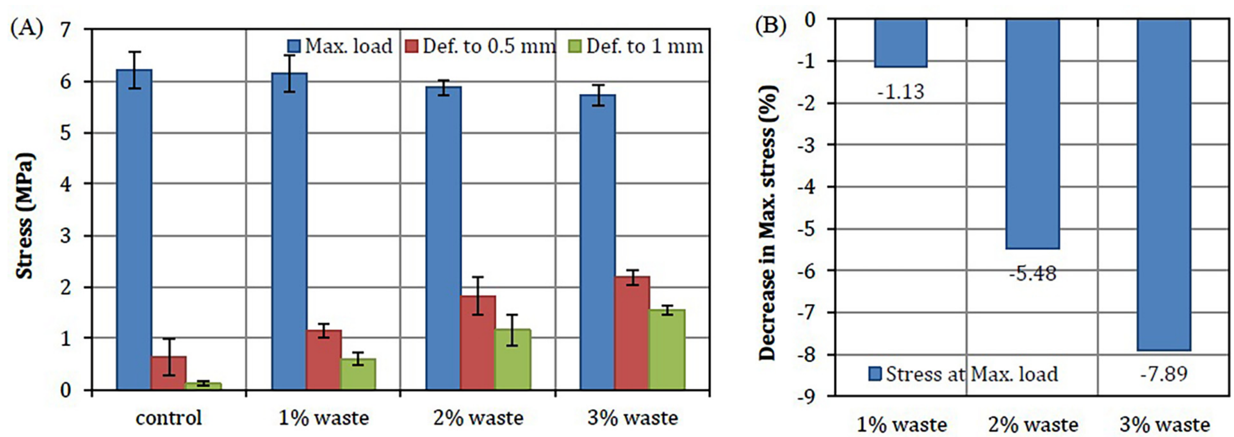

Fig. 8. A) stress at maximum load (flexural strength), deflection to 0.5 mm and 1.0 mm for the concrete samples with different waste contents, B) decrease in flexural strength of concrete by addition of carpet waste cuttings.

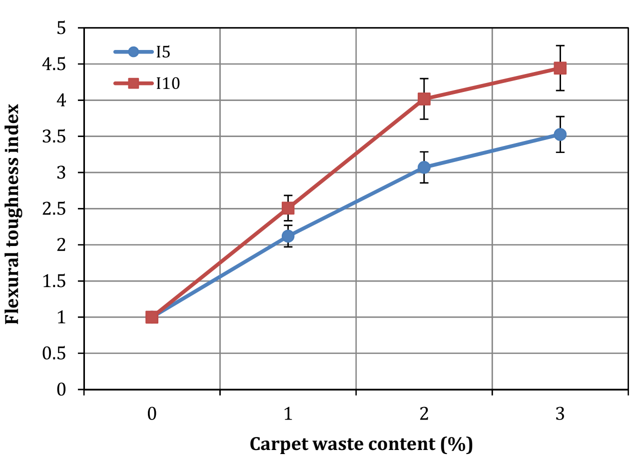

Fig. 9. Toughness indices of the concrete samples (I5 and I10) with different contents of carpet waste.

Fig. 10. Crack bridging action of a carpet waste particle.

$$I_5 = (A_1 + A_2)/A_1 \quad (3)$$

$$I_{10} = (A_1 + A_2 + A_3)/A_1 \quad (4)$$

where A_1, A_2 and A_3 are the corresponding areas under the flexural load-deflection curve to the mid-span deflection of δ_p, 3 δ_p and 5.5 δ_p, respectively. As indicated in Fig. 9, increasing the carpet waste content in the concrete sample leads to enhanced toughness index. This is connected to increasing the carpet wastes which are available for effective bridging. Carpet wastes play an important role in bridging the cracks developed under loading. Fig. 10 illustrates crack bridging action of a carpet waste particle.

3.5. Water absorption

Water absorption of the concrete samples has been measured and shown in Fig. 11A. According to the results, water absorption of samples lies between 6.8% and 9.3%. The percentage increment in water absorption of concrete by increasing the carpet waste content is demonstrated in Fig. 11B. Clearly, addition of the carpet waste even in a small content has remarkably increased water absorption of the concrete sample. This is due to higher porosity of this type of waste materials. It is worth noting that water absorption of carpet waste is mainly physical.

Fig. 12A exhibits the presence of carpet waste particles in the cross-section of a concrete sample. Microscopic observation indicated that waste particles are perfectly combined with cementitious matrix and there is no distinct interface zone (boundaries) between the carpet waste and the matrix (Fig. 12B). As shown in Fig. 13, hydrated cement products have completely penetrated into the fibrous structure of carpet waste. Filling up of these interstitial spaces plays an important role in enhancement of bonding strength of the waste particles with matrix. Due to the good bonding property of carpet waste with concrete matrix, they can effectively act in load-bearing capacity of concrete in post-peak region. The empty spaces between the fibers can provide ideal sites for penetration of hydration products.

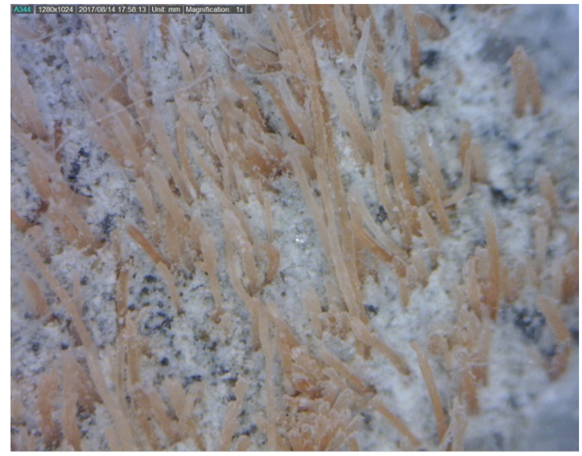

Fig. 13. Penetration of cement hydrated products into fibrous structure of the carpet waste.

As observed from the investigation, the treated needle-felt carpet wastes exhibit crack bridging ability. Their performance is similar to short and randomly distributed virgin fibers in concrete materials. However, the effect of weight reduction of concrete in the case of carpet wastes is more pronounced than that of virgin short fibers due to lower density of the carpet wastes.

In term of cost, it is worth noting that the cost of virgin polypropylene fiber for concrete usage is approximately 1.7 $

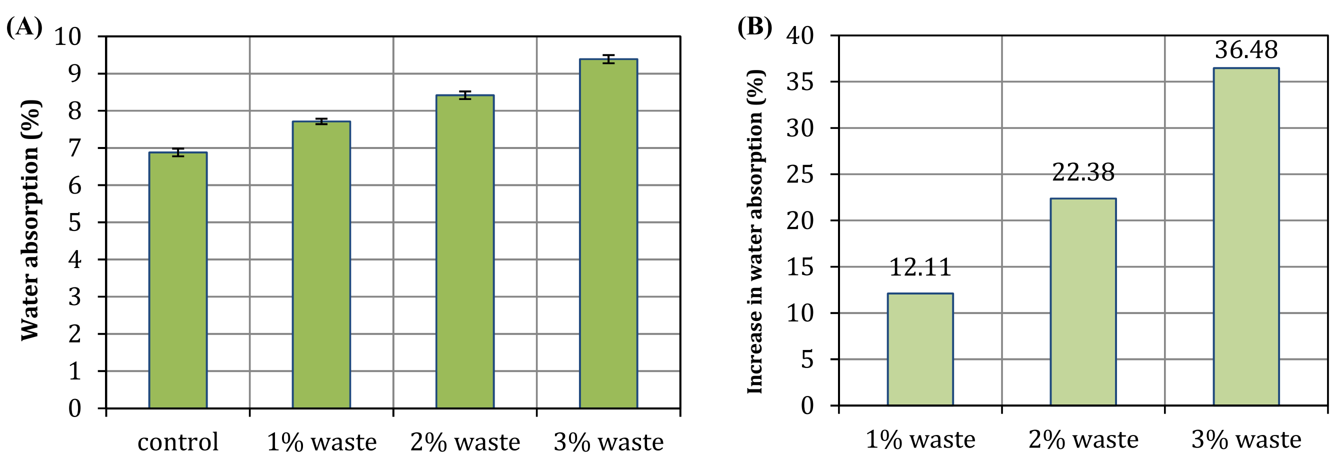

Fig. 11. Water absorption of the concrete samples, A) water absorption values, B) increase in water absorption with respect to the control sample.

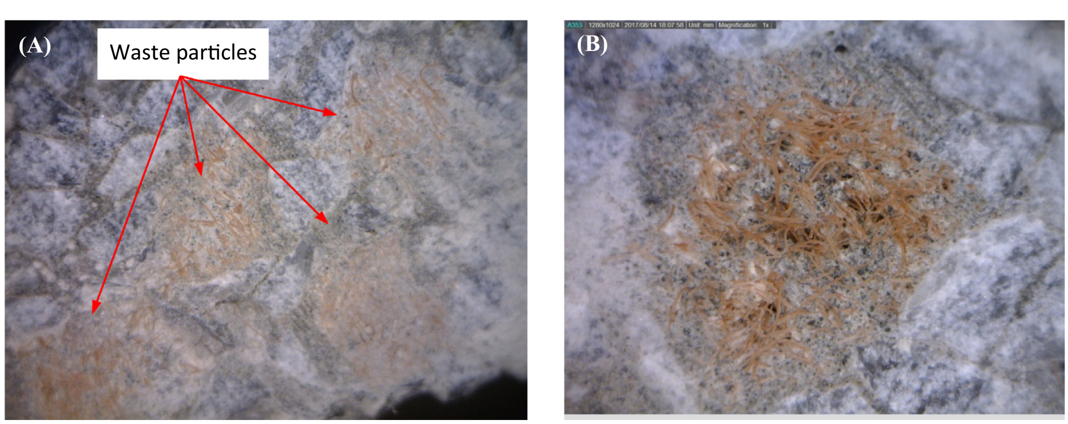

Fig. 12. Concrete containing carpet waste cuttings: A) cross-section of a fractured surface, B) boundary between the carpet waste and concrete matrix.

per kg. Therefore, the cost of used virgin fibers for production of a lightweight concrete per cubic meter is assumed to be 15.5 $. However, the use of modified carpet waste in concrete as examined in the present work requires no additional cost for production of a lightweight concrete. In this respect, it is recommended that carpet waste cuttings can be used as replacement of both virgin fibers and lightweight aggregate.

4. Conclusion

In this study, the effect of treated needle-felt carpet waste cuttings as lightweight aggregates in concrete was studied. The influence of carpet waste content on physical and mechanical performance of concrete was investigated through an experimental testing program. The study demonstrated that treated needle-felt carpet waste cuttings due to their low density and fibrous structure can be used as effective materials intended for both weight reduction and improving post-cracking behavior of concrete. The following conclusions are drawn from the present study:

- Surface coating of needle-felt carpet waste increased its dimension stability as well as tensile strength and load-bearing capacity under flexural load.
- Incorporation of even a small content of needle-felt carpet waste cuttings into mixture significantly reduces density of concrete. Density of concrete with 3% of carpet waste cuttings was decreased by 14% in comparison to control sample.
- Similar to other type of plastic materials, incorporation of this type of waste into mixture reduces compressive and flexural strength of concrete. According to the results, compressive strength is more influenced by carpet waste addition.
- The needle-felt carpet waste cuttings due to their fibrous structure can effectively bridge the cracks. This mechanism significantly improves load-bearing capacity of lightweight concrete in post-peak region and flexural toughness.

It can be concluded that this type of treated waste can be used as promising candidates for production of lightweight concretes. It is worth mentioning that the use of coated needle-felt carpet waste in concrete products could serve as an alternative solution to waste disposal. Furthermore, the reuse of this type of fibrous waste in concrete contributes to cleaner environment and production of low cost and low weight building elements.

Conflict of interest

None of authors have the conflict of interest.

Acknowledgements

The authors would like to express their sincere thanks to Iran National Science Foundation (INSF) for their support given through research Grant number of 93009023.

References

[1] Janet Herlihy, Floor Covering Weekly; Statistical report 2017, Hearst Business Media, New York, NY, USA, 2018.
[2] A. Carmichael, Man-Made Fibers Continue to Grow, Textile World (online), 2015. retrieved from: https://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow/.
[3] S.J. McNeil, M.R. Sunderland, L.I. Zaitseva, Closed-loop wool carpet recycling, Resour. Conserv. Recycl. 51 (1) (2007) 220–224.
[4] Y. Wang, Fiber and textile waste utilization, Waste Biomass Valor 1 (2010) 135–143.
[5] Y. Wang, Y. Zhang, M. Polk, S. Kumar, Recycling of carpet and textile fibers, John Wiley & Sons, New York, 2003, pp. 697–725.
[6] U. Europea, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, European Community, Brussels, Belgium, 2008.
[7] Communication from the Commission, Roadmap to a Resource Efficient Europe, COM/2011/0571, 2011.
[8] Towards a circular economy: A zero waste programme for Europe. COM, 398 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 2.7.2014, 2014
[9] P. Lemieux, E. Stewart, M. Realff, J.A. Mulholland, Emissions study of co-firing waste carpet in a rotary kiln, J. Environ. Manage. 70 (1) (2004) 27–33.
[10] M. Mirzababaei, M. Miraftab, M. Mohamed, P. McMahon, Unconfined compression strength of reinforced clays with carpet waste fibers, J. Geotech. Geoenviron. Eng. 139 (3) (2013) 483–493.
[11] B.J. Putman, S.N. Amirkhanian, Utilization of waste fibers in stone matrix asphalt mixtures, Resour. Conserv. Recycl. 42 (3) (2004) 265–274.
[12] M. Mirzababaei, M. Miraftab, M. Mohamed, P. McMahon, Impact of carpet waste fibre addition on swelling properties of compacted clays, Geotech. Geol. Eng. 31 (1) (2013) 173–182.
[13] R. Siddique, J. Khatib, I. Kaur, Use of recycled plastic in concrete : A review, Waste Manage. 28 (10) (2008) 1835–1852.
[14] J.M.L. dos Reis, Effect of textile waste on the mechanical properties of polymer concrete, Mater. Res. 12 (1) (2009) 63–67.
[15] H. Schmidt, M. Cieslak, Concrete with carpet recyclates: suitability assessment by surface energy evaluation, Waste Manage. 28 (7) (2008) 1182–1187.
[16] Y. Wang, Utilization of Recycled Carpet Waste Fibers for Reinforcement of Concrete and Soil, Polym.-Plast. Technol. Eng. 38 (3) (1999) 533–546.
[17] A. Sotayo, S. Green, G. Turvey, Carpet recycling: a review of recycled carpets for structural composites, Environ. Technol. Innov. 3 (2015) 97–107.
[18] T. Choi, Environmental impact of voluntary extended producer responsibility: The case of carpet recycling, Resour. Conserv. Recycl. 127 (2017) 76–84.
[19] H. Mohammadhosseini, A.S.M.A. Awal, Physical and mechanical properties of concrete containing fibers from industrial carpet waste, Int. J. Res. Eng. Technol. 2 (2013) 404–468.
[20] M. Ucar, Y. Wang, Utilization of recycled post consumer carpet waste fibers as reinforcement in lightweight cementitious composites, Int. J. Cloth. Sci. Technol. 23 (4) (2011) 242–248.
[21] K. Aghaee, M. Foroughi, Construction of lightweight concrete partitions using textile waste, in: ICSDEC 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction, 2013, pp. 793–800.
[22] Y. Wang, A.H. Zureick, B.S. Cho, D.E. Scott, Properties of fibre reinforced concrete using recycled fibres from carpet industrial waste, J. Mater. Sci. 29 (16) (1994) 4191–4199.
[23] H. Schmidt, M. Cieślak, Concrete with carpet recyclates: Suitability assessment by surface energy evaluation, Waste Manage. 28 (7) (2008) 1182–1187.
[24] M. Miraftab, R. Horrocks, C. Woods, Carpet waste, an expensive luxury we must do without!, AUTEX Res J. 1 (1) (1999) 1–7.
[25] I.M. Rushforth, K.V. Horoshenkov, M. Miraftab, M.J. Swift, Impact sound insulation and viscoelastic properties of underlay manufactured from recycled carpet waste, Appl. Acoust. 66 (6) (2005) 731–749.
[26] J.L. Ruiz-herrero et al., Mechanical and thermal performance of concrete and mortar cellular materials containing plastic waste, Constr. Build. Mater. 104 (2016) 298–310.
[27] Z.Z. Ismail, E. A. AL-Hashmi, Use of waste plastic in concrete mixture as aggregate replacement, Waste Manage. 28 (11) (2008) 2041–2047.
[28] S.C. Kou, G. Lee, C.S. Poon, W.L. Lai, Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes, Waste Manag. 29 (2) (2009) 621–628.
[29] E. Rahmani, M. Dehestani, M.H.A. Beygi, H. Allahyari, I.M. Nikbin, On the mechanical properties of concrete containing waste PET particles, Constr. Build. Mater. 47 (2013) 1302–1308.