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Waste management by recycling of polymers with reinforcement of metal powder

Rupinder Singh [a], Narinder Singh [a], Francesco Fabbrocino [b], Fernando Fraternali [c, *], I.P.S. Ahuja [d]

[a] Department of Production Engineering, Guru Nanak Dev Engineering College, Ludhiana, India
[b] Pegaso University, Department of Engineering, Piazza Trieste e Trento, 48, 80132 Naples, Italy
[c] Department of Civil Engineering, University of Salerno, Italy
[d] Department of Mechanical Engineering, Punjabi University, Patiala, India

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A B S T R A C T

Recycling of plastics/polymers is one of the waste management techniques which have been followed by many researchers. In past 20 years large number of applications in this field has been highlighted. But hither to very few have reported on plastic waste management by recycling of polymers with reinforcement of metal powder. In the present work an effort has been made to perform recycling of waste plastic/polymer with reinforcement of metal powder by controlling the melt flow index (MFI). The present study of recycling of waste plastic has been performed on single screw extruder machine by considering various input parameters (namely: barrel temperature, die temperature, and screw speed/rpm). Investigations were performed for the parametric optimization of single screw extruder machine for different mechanical/metallurgical properties (like: porosity, peak elongation, break strength, Shore D hardness) with the help of case study of recycled high density polyethylene (HDPE)100%, HDPE90% + Fe10%, low density polyethylene (LDPE)100% and LDPE94 + 6% (by wt.). As HDPE and LDPE do not decompose naturally, this nature makes these polymers suitable for structural applications (like in beams and reinforced concrete cements (RCC) structures).

1. Introduction

Increase in polymer waste is major responsible factor for the hike in production of solid waste with a wide range of high impacts on the environment [1]. Annual consumption of polymer has increased up to 20 times from few million tons in 1950 to around 100 million tons in 2004 [2]. Highly versatile nature, lighter than competing materials and tailor made abilities is major reason for increased use of polymer materials. Further increase in polymer waste is creating pressure on limited space [3]. Therefore scenario has changed being that the polymer waste has to be recycled. Most of the polymer waste is coming out of post consumer based plastic materials. Post consumed plastic material find new possibilities in the area of new product development [4–9]. HDPE and LDPE are most commonly used plastic material in commodities. Recycling is only possible way out to mange polymer waste based on post consumer based products. Recycling consists of four tasks namely collection, separation, reprocessing and marketing [10]. ASTM has put down four types of recycling, Primary, Secondary, Tertiary (chemical, pyrolysis) and Quaternary (incineration). Primary and secondary can be termed as mechanical recycling techniques as it includes recycling of polymer by heating material up to certain temperature and changing its physical shape. But tertiary (chemical, pyrolysis) and quaternary (incineration) consists of somewhat different criteria. In pyrolysis, by-products obtained are of high calorific values but this process consumes high energy [3]. In quaternary recycling incineration with heat recovery, some plastics like PVC must be removed since harmful gases are emitted when burnt in environment. Recycling is method for reducing quantity of discharge of waste stream. Recycling the polymers also has potential to generate remarkable saving in fossil fuel consumption. Recycling of polymer requires less energy as compare to production of same polymer from virgin material [11]. Some recycled polymers has established a great market value in the field of composites [12], auto parts [13], soil reinforcement [14], artificial implants,

* Corresponding author.
E-mail address: f.fraternali@unisa.it (F. Fraternali).

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healthcare applications, medical delivery systems, removal of bacteria and water desalination [15]. Therefore recycling is a rising issue in recent years due to great use of plastic [16]. Reason behind this growth is strength, user-friendly design, fabrication capabilities and low density. Researchers have studied various recycling techniques to prepare products like plastic lumber [17], composites by reinforcing metallic/ceramic materials etc [18]. Basically reinforcements in polymer material can only be done by the mechanical recycling (primary and secondary). Primary recycling is used for uncontaminated materials and secondary may be used for polymers for cheaper applications. So in this study an effort has been made to present a plastic waste management by recycling with reinforcement of metal powder 'Fe' in HDPE and LDPE as matrix material. The Fe powder was mixed with matrix materials and various combinations of different proportions by weight were made. After this MFI, a very important rheological property of polymer material to determine their flow behaviour was studied and established. Thereafter different selected proportions were made to process on single screw extruder and a filament wire of cylindrical shape was made for fused deposition modelling machine (FDM) setup for other high end applications. For the present work filament wires were tested for their mechanical properties. The basic reason behind the reinforcement of Fe powder in polymer waste was to enhance its mechanical properties as well as make it suitable for structural applications. The wire prepared in this work may be used in tying the iron bars in beams and in RCC roofs. The iron wire (usually MS) which is now a day's used does not possess any kind of corrosion resistant property so wire made from polymer waste may be helpful in tying up of iron bars in structures and flexible nature of wire will allow the minor movement of structures. The literature review reveals that the recycling of plastic waste material is a common practice to enhance the reusability of waste polymer for the purpose of managing waste and is widely used in almost every field, particularly in packaging, building and construction, automotive, electrical and electronics, agriculture, and other industries [19,20]. The present study also highlights the various MFI values based on various proportions of waste polymer with Fe powder reinforcement, which may be used as standard data by the future researchers.

2. Experimentation

2.1. Materials and methods

Initially waste HDPE and LDPE was collected from local market. Polymer waste was washed to separate out the contaminants present in waste polymer. After washing of polymer different samples of HDPE and LDPE were taken for the MFI testing.

2.2. Melt flow index

Melt flow index is an analytical method used for determination of quality of polymer and flow properties [21]. Various research studies showed the relationship between the MFI and different physical and chemical properties, such as viscosity, shear strength, molecular weight distribution and shear rate [22–27]. The MFI method is a measure of ability of a polymer or plastic in to flow under certain conditions like pressure and fixed size orifice. Dimensions of orifice, temperature and load pressure are specified by ASTM standards, and then value is measured in grams per 10 min [21]. A basic diagram of melt flow tester machine is given in Fig. 1.

As observed from Fig. 1 the melt flow tester consists of cylinder which is heated by surrounding heater. The heater is covered by insulating material so that the heat loss could be minimized and this heater is processed by automatic controls of machine. This

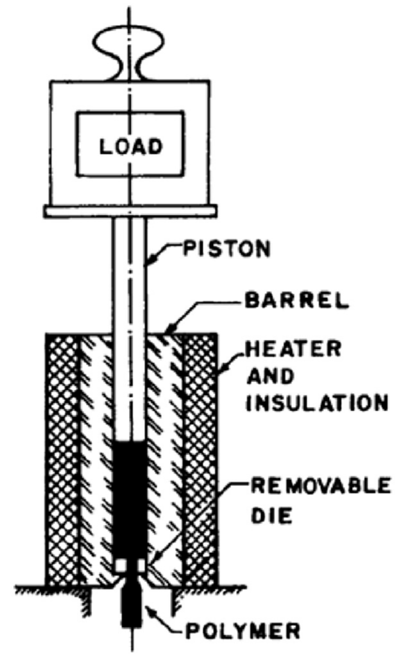


Fig. 1. Schematic of melt flow tester [28].

system consist of standard weights which pressurize the melted material from upper side and forces the material to flow out of die at standard condition. After selection of polymer waste as the matrix material the MFI of HDPE and LDPE was tested with and without reinforcement of Fe powder (see Table 1).

The main objective of this pilot study was to know that how different proportion of Fe powder reinforcement effects the MFI of composite material. Finally fixed proportion were taken for further experimentation on single screw extruder (i.e., HDPE 100%, HDPE 90% + 10% Fe powder, LDPE 100% and LDPE 94% + 6% Fe powder).

2.3. Single screw extruder

In the extrusion process polymers are generally fed from hopper which is gravimetric. The material goes through the hopper and comes in contact with the screw of extruder. The screw is rotating at generally 10 rpm forces the plastic polymer in straight direction inside the barrel. Screw rpm can be controlled by controller unit which are provided with machine. Material is heated by heater mounted on barrel which can range from 120 °C to 300 °C depending on the polymer. Time of cooling and speed of rolling of

Table 1
MFI for HDPE/LDPE and Fe powder in different proportions (by wt).

HDPE	100%	90% + 10%	85% + 15%	80% + 20%	75% + 25%
	17	23.3	20.4	23	25.96
	18.22	23.98	23	24.85	27
	17.56	22.56	25.2	26.08	28
	15.06	17.93	19.23	20.49	23.43
	19.63	22.59	24.83	21.69	22.66
LDPE	**100%**	**94% + 6%**	**90% + 10%**	**80% + 20%**	**70% + 30%**
	2.37	2.69	3.07	3.013	2.855
	2.01	2.78	2.72	3.04	3.53
	2.10	2.68	2.88	2.93	3.51
	2.31	2.75	3.10	3.02	3.26

the material play a major role in dimensional accuracy and properties of the wire being extruded [29]. Three or more independent controlled heating zones gradually increase the temperature of the barrel from the rear end (where the plastic enters) to the front. This allows the plastic polymer to melt easily or effectively as they are forced through the screw rotation and reduces the risk of overheating which may cause overheating of the polymer. When melted material comes out of die it can be rolled in form of wire easily by the rolling unit which is available at machine site as unit of machine. To maintain the uniformity of extruded material, some arrangements are made to preheat the material [30]. Basic screw extrusion setup is shown in Fig. 2.

As observed from Fig. 2 screw extrusion process has number of stages: (i) solids conveying of material in the hopper; (ii) drag solids conveying in the initial turns of the screw; (iii) delay in melting, due to the development of a thin film of melted material separating the solids from the surrounding metallic wall(s); (iv) melting, where a specific melting mechanism develops, depending on the local pressure and temperature gradients; (v) pumping involving the complex but regular helical flow pattern of the fluid elements towards the die; (vi) flow through the die. Initially pilot study has been conducted on single screw extruder and it has been found that various factor like barrel temperature, die temperature and screw speed contributes towards the properties of extrudate. In pilot experimentation L9 orthogonal array (Taguchi approach) has been employed by taking above mentioned parameters into consideration (see Table 2).

Table 2
Control log for experimentation.

Trial run	A	B	C
1	80	120	10
2	80	140	15
3	80	160	20
4	100	120	15
5	100	140	20
6	100	160	10
7	120	120	20
8	120	140	10
9	120	160	15

Where A, B and C are barrel temperature (in °C), die temperature (in °C) and screw speed (rpm) respectively.

3. Results and discussion

Based upon settings of input parameters as per Table 2, wires were prepared on single screw extruder and tested for their mechanical properties (namely; peak elongation, break strength, Shore D hardness). After mechanical testing a statistical package MINITAB software was used for further optimization. For each output, S/N ratio was calculated.

For this different case studies have been discussed simultaneously. At first peak elongation of HDPE 100%, HDPE 90 + 10% has been discussed (See Table 3).

It can be clearly seen from Table 3 that peak elongation in case of reinforced HDPE is better than HDPE 100%. This may be due to the presence of Fe powder. The obtained results for peak elongation were evaluated for 'larger the better' on Minitab software to know which input parameter is most significant. Fig. 3 shows the SN ratio plots for HDPE 100%, HDPE 90 + 10%.

As observed from Fig. 3(a, b), maximum peak elongation is obtained at level 1 of barrel temperature, level 1 of die temperature and level 2 of screw speed. This may be because of the fact that low barrel temperature provides low material pre-heating that resulted into low fluidity, which is duly ensured by moderate rpm of screw. Further low temperature of die resulted into low melting, but sufficient enough (for this material) to come out of die. Further Table 4 provides the analysis of S/N ratio for variance of peak elongation for 100% HDPE.

From Table 4 it can be seen that no input parameter is contributing significantly (since $p > 0.05$) for peak elongation. After analysing the variance for 100% HDPE response table has been obtained for ranking of input process parameters. (see Table 5).

3.1. Optimization of peak elongation (100% HDPE)

After this optimization of the peak elongation was performed mathematically as under:

$$\eta_{opt} = m + (m_{A1} - m) + (m_{B1} - m) + (m_{C2} - m)$$

η_{opt} is the best value for the peak elongation for100% HDPE. 'm' is the mean of S/N data, m_{A1} is the mean of S/N data at level 1 and m_{B1} is the mean of response to the S/N data at level 1 and m_{C2} is the mean of response to the S/N data for level 2.

$$y^2_{opt} = 1/(10)^{-\eta opt/10} \quad \text{for larger is better case}$$

Calculation,

Mean of Signal to noise ratio (m) was taken from Table 3

$m = 4.44$

Now from response table of signal to noise ratio, $m_{A1} = 6.308$,

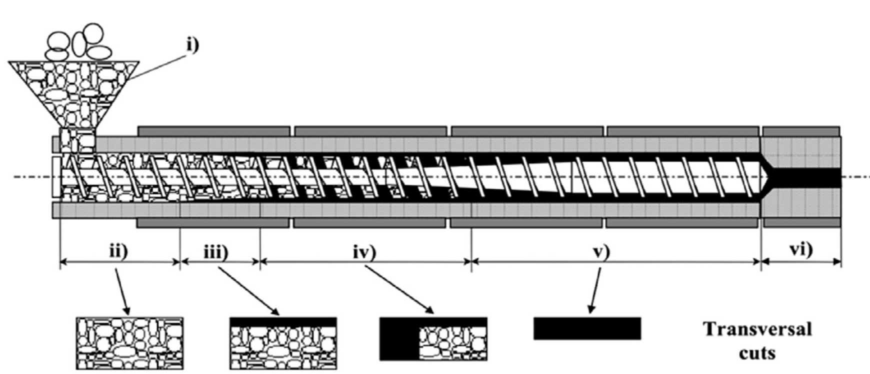
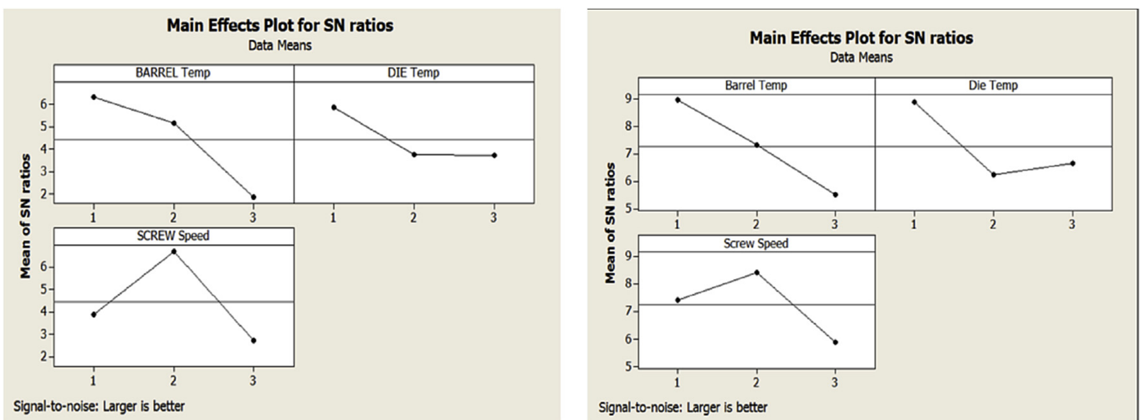


Fig. 2. Single screw extrusion setup [31].

Table 3
Peak elongation data.

Parametric condition	Peak elongation(mm) HDPE 100%	S/N ratio mean HDPE 100%	Peak elongation HDPE 90 + 10%	S/N ration mean HDPE 90 + 10%
1	2.333333	7.354317	3.636667	11.21392
2	2.623333	8.342708	2.656667	8.486453
3	1.466667	3.227626	2.28	7.15853
4	2.556667	8.133408	3.273333	10.29849
5	1.41	2.95656	1.873333	5.433562
6	1.7	4.373684	2.06	6.275923
7	1.296667	2.068442	1.813333	5.146091
8	1.025667	−0.07181	1.743333	4.827514
9	1.516667	3.60449	2.126667	6.551983



HDPE 100% (a) HDPE 90%+10% Fe (b)

Fig. 3. S/N ratio plots for peak elongation for HDPE.

Table 4
Analysis of S/N ratio for variance (100%HDPE).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Barrel Temp	2	31.863	31.863	15.931	14.43	0.065
Die Temp	2	8.931	8.931	4.466	4.04	0.198
Screw Speed	2	24.717	24.717	12.359	11.19	0.082
Residual Error	2	2.208	2.208	1.104		
Total	8	67.719				

$m_{B1} = 5.852$and $m_{C2} = 6.694$.

From here,
$\eta_{opt} = 4.44 + (6.308{-}4.44) + (5.852{-}4.44) + (6.694{-}4.44)$

$\eta_{opt} = 10.03$
Now, to optimize $y^2_{opt} = 1/(10)\text{-}^{\eta opt/10}$

$y^2_{opt} = 1/(10)\text{-}^{10.03/10}$
Yopt = 3.17 mm

So, Optimum peak elongation = 3.17 mm.

Further Table 6 shows analysis of S/N ratio for variance for HDPE 90% + 10% Fe.

F value for barrel temperature is also >9 hence it is significant according to 90% confidence level. Table 7 shows ranking of input process parameters. The optimized value for peak elongation

Table 5
S/N ratio response (Larger is better) (100%HDPE).

Level	Barrel temp	Die temp	Screw speed
1	6.308	5.852	3.885
2	5.155	3.742	6.694
3	1.867	3.735	2.751
Delta	4.441	2.117	3.943
Rank	1	3	2

Table 6
Analysis of S/N ratio for variance for HDPE 90 + 10%Fe.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Barrel Temp	2	17.818	17.818	8.9092	9.26	0.097
Die Temp	2	12.071	12.071	6.0353	6.27	0.137
Screw Speed	2	9.759	9.759	4.8793	5.07	0.165
Residual Error	2	1.924	1.924	0.9619		
Total	8	41.571				

Table 7
S/N ratio response Table (Larger is better) for HDPE90% + 10%Fe.

Level	Barrel temp	Die temp	Screw speed
1	8.953	8.886	7.439
2	7.336	6.249	8.446
3	5.509	6.662	5.913
Delta	3.444	2.637	2.533
Rank	1	2	3

Table 8
Values of break strength for various proportions.

Parametric condition	Strength at break(KN/mm^2) HDPE 100%	S/N ratio mean	Strength at break HDPE (90 + 10%)	S/N ratio mean
1	12.21	21.7343	15.02333	23.53532
2	11.00667	20.83053	9.87	19.88306
3	8.29	18.36995	13.88667	22.8515
4	9.866667	19.87959	4.32	12.70793
5	7.02	16.92583	6.483333	16.23571
6	6.733333	16.55615	6.36	16.06848
7	7.56	17.57015	8.53	18.61789
8	6.676667	16.49117	5.576667	14.91731
9	10.34	20.28722	7.05	16.96356

Table 9
Shore D hardness values.

Parametric condition	Shore D hardness HDPE 100%	S/N ratio mean	Shore D hardness HDPE (90 + 10%)	S/N ration mean
1	48.66667	33.73596	48	33.62105
2	40.83333	32.21723	44	32.86457
3	40.33333	32.11152	49.5	33.88856
4	51	34.14806	47.1	33.47044
5	36.33333	31.19711	47.3	33.4861
6	39.16667	31.85506	52.2	34.35486
7	48	33.62105	49.3	33.86229
8	36.66667	31.16512	45.7	33.19002
9	36	31.10666	49.2	33.85073

Table 10
Values of different properties for LDPE 100% and reinforced LDPE 94% + 6%.

Trial run	Peak elongation LDPE 100%	S/N ratio LDPE 100%	Peak elongation LDPE (94% + 6%)	S/N ratio LDPE (94% + 6%)	Break strength LDPE 100%	S/n ratio LDPE 100%	Break strength LDPE (94% + 6%)	S/n ratio LDPE (94% + 6%)	Shore D hardness LDPE 100%	S/N ratio LDPE 100%	Shore D hardness LDPE (94% + 6%)	S/N ratio LDPE (94% + 6%)
1	130.4533	42.30904	116.38	41.31753	6.236667	15.89762	6.576667	16.35971	25.6	28.16309	36.83333	31.32428
2	129.0667	42.21552	116.58	41.33164	8.39	18.47302	7.24	17.19475	29	29.02889	38.83333	31.78361
3	140.3733	42.94567	115.8333	41.27666	6.69	16.50637	5.246667	14.39763	32.5	30.23561	43.33333	32.73014
4	126.3833	42.0338	115.5733	41.25694	6.33	16.0177	8.373333	18.4439	25.46667	27.76779	32.9	30.30832
5	160.2433	44.0956	115.2367	41.23117	5.176667	14.28067	6.316667	16.00903	23.33333	27.3501	35.1	30.84892
6	120.7667	41.63881	118.685	41.48788	3.846667	11.69404	5.83	15.31227	25	27.94489	41.06667	32.26561
7	140.4033	42.9475	120.2533	41.60191	5.766667	15.21638	8.366667	18.44813	21.76667	26.66816	32.93333	30.34594
8	150.3033	43.53937	121.27	41.67504	5.206667	14.33106	6.23	15.88967	22.63333	26.79439	35.33333	30.95918
9	140.2	42.9349	118.1	41.44481	6.536667	16.28678	7.266667	17.21969	26.93333	28.5992	37.3	31.43189

calculated mathematically (as in previous case of HDPE 100%) for HDPE 90% + 10%Fe is 3.86 mm.

The break strength and Shore D hardness for HDPE 100%, HDPE 90% + 10% Fe has been calculated (see Table 8).

The calculated value of optimum break strength for HDPE 100% and HDPE 90% + 10% Fe is 15.41 kN/mm^2 and 15.85 kN/mm^2 respectively.

Table 9 shows Shore D hardness values for HDPE 100% and HDPE 90% + 10% Fe.

The calculated value of optimum shore D hardness for HDPE 100% and HDPE 90% + 10% Fe is 51.98 and 51.68 respectively.

The similar exercise was performed for all these properties in case of LDPE 100% and LDPE 94% + 6% Fe (see Table 10).

The optimized value of peak elongation in case of LDPE100% was 166.14 mm and 120.9868 mm for reinforced LDPE 94% + 6%. Further optimized value of break strength has been obtained as 8.68 kN/mm^2 for LDPE100% as compared to reinforced LDPE 94% + 6% which has value of 8.75 kN/mm^2. Finally optimized value for shore D hardness was 33.17 for LDPE 100% and 44.38 shore D was obtained in case of LDPE94% + 6%. Fig. 4(a) and (b) respectively shows porosity results at magnification of 100× for HDPE 100%,HDPE 90 + 10%Fe, LDPE 100% and LDPE 94% + 6%Fe.

As observed from Fig. 4(a), minimum 3.75% porosity was obtained in trial run 2 and maximum porosity was obtained in trial run 8 i.e. 14.23%. Less is the porosity better will be the mechanical properties of material. For example in case of maximum porosity there will be least peak elongation. As observed from Table 3 peak elongation is lowest for trial run 8 and from porosity results given above one can see that porosity value for HDPE is also more. From Table 3 peak elongation value for trail run 2 is maximum hence from porosity results its percentage porosity is also lowest.

From Table 10 it can be seen that peak elongation is lowest for trial run 4 so from porosity results given in Fig. 4(b) one can see that porosity value for LDPE 100% is also greater than any other value. From Table 10 peak elongation value for trail run 5 is maximum; hence from porosity results its percentage porosity is also lowest. Since in case of reinforced LDPE 94% + 6% minimum porosity level has been obtained at trial run 8 and in Table 10 maximum value for peak elongation has been obtained at same trial run. Similarly porosity graphs can be compared with other properties for counter verifications.

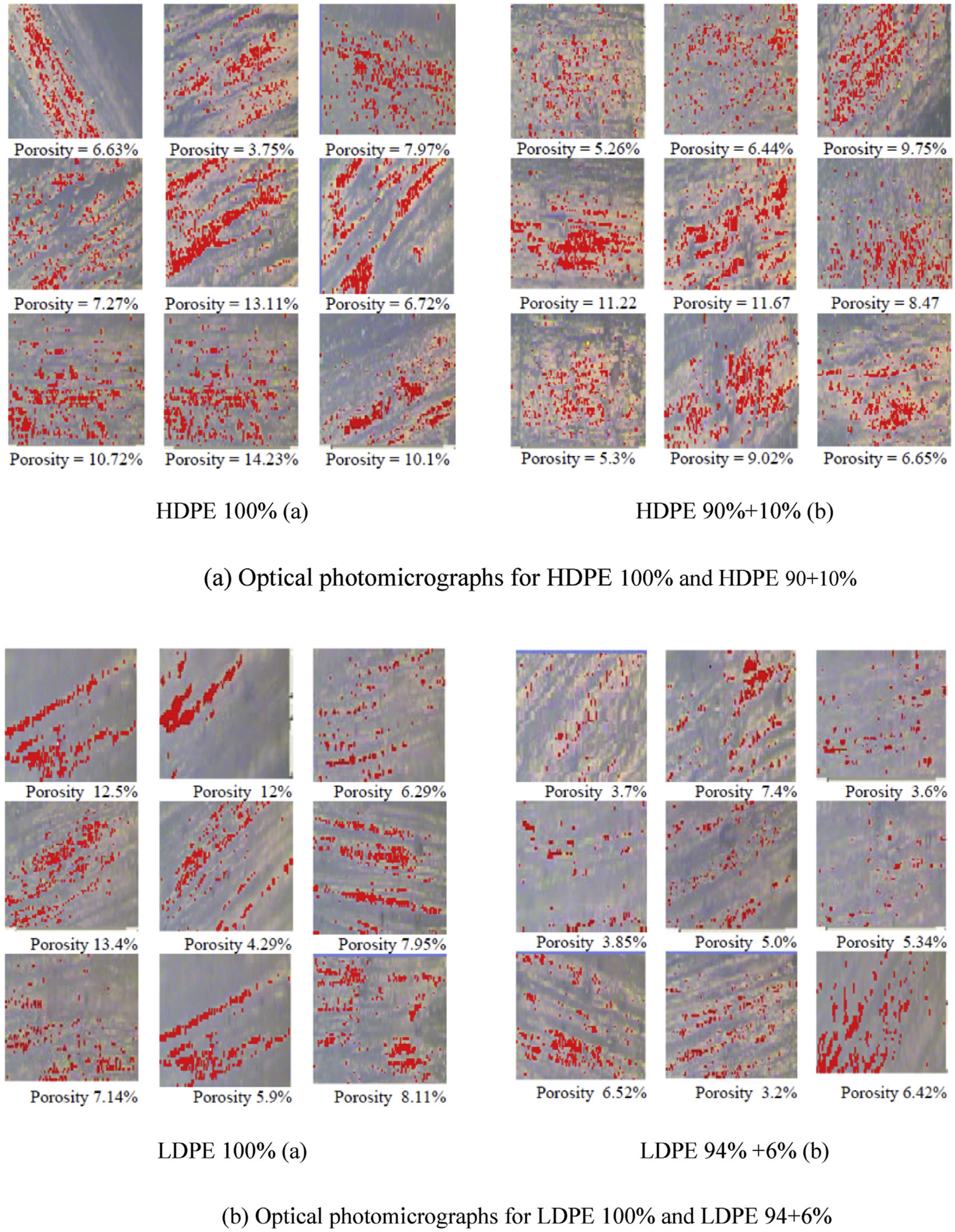


Fig. 4. (a) Optical photomicrographs for HDPE 100% and HDPE 90 + 10%. (b) Optical photomicrographs for LDPE 100% and LDPE 94 + 6%.

4. Conclusions

In the present research work the parametric optimization for single screw extrusion has been done for preparation of Fe powder reinforced polymer wire. Further separate case studies for HDPE 100%, HDPE90% + 10%Fe, LDPE 100% and LDPE 94% + 6% Fe powder reinforcement have been outlined. From this study it has been concluded that polymer waste mainly HDPE and LDPE can be successfully used for structural engineering applications by preparing filament wire with screw extrusion route along with the metal powder reinforcement. The mechanical properties like (peak elongation, break strength and shore D hardness) and metallurgical property like porosity can be controlled based upon specific application. In case of reinforced HDPE i.e. 90% HDPE and 10% Fe powder, the mechanical properties obtained were better. Further porosity obtained was lowest in case of 100% HDPE. Further in case of LDPE, 100% LDPE gives better results for peak elongation but in case of strength at break and shore D hardness reinforced LDPE gives better result. The results of study suggest that reinforcement of metal powder in polymer waste enhances the properties of polymer up to an appreciable extent.

We address studies dealing with the use of metal-reinforced sustainable polymers within cement-matrix structures [32–40], and lattice metamaterials [41–44] to future work.

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