


Improving chemical and hydro-physical properties of semi-arid soils using different magnitudes of crumb rubber

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Abstract

Purpose Iran is located on the desertification strip where it has faced water shortage and poor quality soils. So it is necessary to improve the soil structure and increase irrigation efficiency. In this context, the use of industrial wastes can increase soil's organic matter and improve its structure, also amend environmental problems related to disposal of industrial wastes. The objective of this study was to survey the effect of crumb rubber (CR) application as soil amendment on soil water retention curve indices, soil aggregate stability and soil micronutrients.

Methods In this study, different amounts of CR (0, 0.12, 0.24, 0.36 and 0.48 g) were added to every kg of the two different soil textures (loamy sand and silty clay). Pots were kept at FC moisture conditions for 6 months. At the end of incubation time, the different soil micronutrient availability, soil structural stability and soil hydraulic properties were measured.

Results The results showed that application of CR as soil amendment had significant effects ($p < 0.001$) on increasing soil organic matter content and soil micronutrient availability including Zn and Fe. Adding CR particles by reducing the aggregate fractal dimension, soil penetration resistance and bulk density, improves soil structure in both types of soil. The results also demonstrated that the use of CR particles can improve water

holding capacity in sandy soil and increased plant available water content and air capacity in clay soil ($p < 0.001$).

Conclusions According to our results adding CR particles can be considered as a low-cost solution in order to improve the hydro-physical and chemical properties of soils in these areas.

Keywords Aggregate stability · Crumb rubber · Penetration resistance · Plant available water content · Soil water retention curve

Introduction

Soil properties are the crucial factors for crop production (Dotaniya et al. 2016). Soils in arid and semi-arid regions are often characterized by low clay and organic matter contents which results in low water holding capacity and inherently low fertility (Abdelfattah 2013). In order to improve soil structure and to increase under cultivation areas in arid and semi-arid regions, there are various management methods such as adding soil amendments, mulches and conservation tillage (Roper et al. 2013; Zhao et al. 2011; Bhatt et al. 2016).

Saline and sodic soils in arid and semi-arid areas cause unfavourable soil physical and chemical properties, which would impose restrictions on plant growth (Jalali et al. 2017). So the applications of appropriate soil amendments result in improving soil properties and reduced soil salinity and other stresses (Courtney and Harrington 2012; Bhattacharjya et al. 2016).

Different synthetic polymers are used for soil amendments in the agriculture which are safe and non-toxic and will eventually decompose to carbon dioxide, water, ammonia and potassium ions. Applying water-absorbing

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soil amendment may improve soil structure, arise water storage and decrease other water-related limitations (Huettermann et al. 2009).

Due to shortage of natural organic matters in arid and semi-arid regions, the use of organic polymers to improve soil structure was very important over the past years and these polymers have shown their ability as soil amendments. In fact, soil management practices encourage the addition of organic matter to the soil which has significant effect on soil physical and chemical properties (Weyers and Spokas 2014).

Previous studies demonstrated positive changes in several soil physical, chemical and biological properties after the addition of organic amendments to soil (Faust et al. 2015; Pandian et al. 2016; Adrover et al. 2017). The improvement of crop productivity has been attributed to the increase in the soil available nutrients (Lia et al. 2017; Chaudhuri et al. 2016; Rajaie and Tavakoly 2016) and enhanced soil physical properties such as reduction in soil bulk density and soil penetration resistance (Saglam and Dengiz 2017) and increase in water-holding capacity after applying soil amendments (Emami et al. 2014; Parihara et al. 2016).

Unfortunately, in some arid and semi-arid areas, natural organic matter is either unavailable or scarce; as an example more than 70 percent of Iran's agricultural soil contains less than 0.5 percent organic matters and ingredient (FAO 2012); thus, improvement of soil structure may be achieved using synthetic polymers (Masowa et al. 2016; Park et al. 2015).

Of the annual total global production of rubber material, which amounts to more than 10 million tons, approximately 60–70% is used in tyre. After they have been worn-out during their limited service life, millions of used tyres are discarded every year. As polymeric materials, rubbers do not decompose easily. Large amounts of waste rubber materials discarded pose two major problems: waste of valuable rubber and disposal of waste rubber leading to environmental pollution. Two major ways to solve the problem are recycling and reusing the waste rubber and reclaiming rubber's raw materials (Zhao et al. 2009).

Crumb rubber (CR) is a secondary resource recycled from scrap automobile tires. This amendment contains graded rubber granules and sometimes additional components, such as compost or mineral materials. The Application of waste polymer such as CR into soil behaves as reinforcement factor in improving soil function. Applying waste plastic for reinforcement of soil is an efficient and reliable technique for improving the strength and stability of soils (Sivakumar Babu et al. 2008). In this area, the amount and size of CR are the most effective factors which determine the soil structure stability from both agriculture and engineering point of view.

CR is not truly inorganic; it behaves much in the same way. Amendments with coarse grade CR can reduce compaction stress in soil, increase total porosity and enhance water movement. Finer particle sizes are being used for topdressing and can protect the crown tissue of plants from abrasion (Groenevelt and Grunthal, 1998). Vanini and Rogers (1995), used the rubber crumb as a soil amendment in different turfgrass situations.

Groenevelt and Grunthal (1998) pointed out that 10–20% of CR significantly reduced surface hardness of sports turf. Riggle (1994) also stated that the inclusion of rubber particles in soil could improve soil physical properties such as aeration and water infiltration rates. He concluded that the water use efficiency and fertilizers were improved by up to 30%. Intention to reuse the abandoned tires by grinding them into small particles (crumb rubber) and using them in sports field, pavement and construction materials may be an important approach to reduce waste rubbers in large quantities (Yilmaz and Degirmenci 2009).

Zhao et al. (2011) investigated the effect of CR waste as a soil conditioner on the nematode assemblage and some soil properties in a turfgrass soil. Their results demonstrated that CR incorporation significantly decreased plant parasite and omnivorous nematode populations, but increased the abundance of predatory nematodes, and also CR application decreased soil bulk density and pH value, while soil moisture content increased.

Taheri et al. (2011) reported that ground tyre rubber and rubber ash were very effective amendments to increase the DTPA-extractable Zn in a calcareous Zn-deficient soil. Khoshgoftarmanesh et al. (2012) investigated the effect of acid-washed shredded waste-tire rubber in hydroponic tomato production. They said shredded waste rubber might be used as a component of container media in production of hydroponically grown tomato; however, acid-washing of rubber is required to prevent potential Zn toxicity for plant.

Pérez et al. (2012) investigated the use of rubber crumbs as drainage layer in green roof establishment. The results of their research raised the possibility of using recycled rubber from tires as a drainage layer in green roofs, substituting the porous stone materials currently used.

Several studies have been carried out throughout the world to identify the effects of incorporating different soil amendment and organic matter into soil and survey their effect on soil's physical and chemical properties. However, various potential use of CR and its environmental impacts have been less investigated and there have been no published investigations about using CR effects on some soil's physical and chemical properties in arid and semiarid region soils. Therefore, the objective of this study was to assess the impacts of waste CR as soil amendment on the soil hydro-physical and chemical properties in arid and semiarid soils. The investigations may provide a basis for



mitigating the worn out tires' pollution problems in the environment, while enhancing some soil's chemical and hydro-physical properties of semi-arid soils.

Materials and methods

The study site and soil properties

This study was carried out in the research greenhouse of the Shahid Bahonar University of Kerman, southeast of Iran (latitude of 30°14'N and longitude of 57°06'E). Kerman and the surrounding regions have a semi-moderate and dry climate with mean annual rainfall of 153 mm (Yazdanpanah et al. 2016). Two different soil textures [loamy sand (S) and silty clay (C)], were collected and air-dried and passed through a 2-mm sieve and stored at room temperature before use.

Physical and chemical properties of the soil samples were quantified in our laboratory. Soil particle size distribution was determined using the hydrometer method (Gee and Bauder 1986), and organic carbon (OC) was measured using the wet-digestion method (Walkley and Black 1934). Soil electrical conductivity (EC) and reaction (pH) were determined in a soil–water extract of 1:5 w:v.

EDTA-extractable elements (Zn, Fe and Cu) were determined by atomic absorption spectrometry (AAS) (Quevauviller et al. 1996) and bulk density was determined with core sample (Blake and Hartge 1986), respectively. The properties of CR particles (with a diameter of less than 2 mm) used in these experiments are presented in Table 1 (Asadollah zadeh 2013). The cation exchange capacity (CEC) of used CR particles was reported about 57 cmol⁺ kg⁻ (Khoshgoftarmanesh et al. 2012).

Preparation of test pots

In this study, the pots with a capacity of 6 kg were used. The test substrates were prepared by adding 0, 0.12, 0.24, 0.36 and 0.48 g CR (with a diameter of less than 2 mm) to every kg of the two different soil textures. The soil and CR were manually blended and transferred to close-end pots without drainage. The pots were stored at greenhouse temperature conditions (23 ± 2 °C) and humidity of field capacity for 6 months before being used to prepare the test samples. Depending on the soil type, specific climate conditions and Intended land-use, different researchers have reported different incubation period from at least

3 months (Zhao et al. 2011), 8 months (Bidaki et al. 2012) and 11 months (Smolders and Degryse 2002), so in this study, the mean of the periods reported (6 months) were selected as the incubation period.

Measuring soil physical properties

Penetration resistance (PR)

Penetration resistance (PR) is a suitable indicator for identifying changes in soil resistance to penetration over a period and for assessing the effects of soil resistance to root development (O'Sullivan 1992). After incubation time, at the end of the test, the samples were irrigated to field capacity water content, and penetration resistance of the samples was determined by penetrometer device (33-T0165 model, CONTROLS Inc).

Depending on the type of soil texture, 0.2 square inch metal cap was used for loamy sand (S) and 0.1 square inch metal cap were used for silty clay (C) samples. Penetrometer probe was immersed to a certain extent (depth of 3 cm) at a nearly constant speed in soil samples. Soil penetration resistance was calculated using the function employed by Tormena et al. (1999) as:

$$PR = \frac{0.5X}{Y} \times \alpha, \quad (1)$$

where PR is the soil penetration resistance (MPa), X is registered device number (mm), Y is cross-sectional area of used metal cap (square inch) and α is acceleration gravity (9.8 ms⁻²).

Soil aggregate stability

Soil aggregate stability was determined by mean weight diameter index (MWD) and Fractal dimension by using Eqs. 2 and 3 (Calero et al. 2008).

$$MWD = \sum_{i=1}^n x_i w_i, \quad (2)$$

where X_i is the mean diameter of any particular size range of aggregates separated by sieving (mm), and W_i is the weight of the aggregates in that size range as a fraction of the total dry weight of the sample. The summation accounts for all size ranges, including the group of aggregates smaller than the openings of the finest sieve.

Table 1 Selected physical and chemical properties of crumb rubber (CR) particles

EC (dS m ⁻¹)	pH (-)	Zn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Cu (mg kg ⁻¹)	Cd (mg kg ⁻¹)	ρ_b (g cm ⁻³)
0.354	6.82	12,000	108	4.25	2.25	0.2



Fractal dimension index of soil aggregates was calculated based on the size-number equation of Turcotte (1989) as follows:

$$N_i = cX_i^{-D} \quad (3)$$

where X_i is the mean diameter of remaining aggregates on each sieve (mm) and c is constant coefficient. Fractal dimension (D) was obtained through regression analysis between $\log N_i$ and $\log X_i$. The amount of N_i is determined from stable aggregate distribution and it will be determined at the end of sieving as follows (Eq. 4 and 5):

$$N_i = \sum_{i=1}^n n_i, \quad (4)$$

$$n_i = w_i \rho^{-1} \times x_i \rho^{-3}, \quad (5)$$

where n_i , ρ and w_i are the number of aggregates, aggregate bulk density and the remaining aggregate mass on each sieves, respectively.

Soil hydraulic properties

Water retention curve is one of the main soil hydraulic properties. It can be considered as a soil's fingerprint, since the shape of the curve is related to various physical and chemical soil properties, which are unique for each soil (Cornelis et al. 2001). Therefore, any change in soil structure will appear in soil water retention curve. In this research, the widely used model of van Genuchten (1980) was fitted to the data obtained from pressure plate apparatus.

Different physical quality indicators derived from water retention curve have been proposed and validated by several authors. Reynolds et al. (2007) found that air capacity (AC) and relative water capacity (RWC) could be good indicators because they responded to different soil management practice, so in this research air capacity, relative water capacity and plant available water capacity (PAWC) were considered.

According to Reynolds et al. (2007), AC is the difference between saturation water content and water content at field capacity (FC). PAWC is the difference between FC and permanent wilting point (PWP). RWC is the ratio of water content at FC to water content at saturation.

Statistical analyses

Current research was carried out with five different CR application rates (0, 0.12, 0.24, 0.36 and 0.48 g kg⁻¹) for two texturally differentiated soil which were named C_0 , $C_{0.12}$, $C_{0.24}$, $C_{0.36}$ and $C_{0.48}$ for silty clay soil and S_0 , $S_{0.12}$, $S_{0.24}$, $S_{0.36}$ and $S_{0.48}$ for loamy sand (S). These pots were

arranged in a randomized complete block design with three replicates.

Statistical assessments of possible difference in soil's physical and chemical properties due to the five rates of CR treatment were analysed with one way-ANOVA by using the SAS program (SAS Institute 1996). Duncan's multiple range test was used to compute LSD values for comparing differences between pairs of treatment means

Results and discussion

Amending the soil chemical properties with CR

Electrical conductivity (EC) and soil reaction (pH)

Table 2 shows physical and chemical properties of the studied soils. Statistical analyses of CR particles' addition on soil physical and chemical properties are presented in Table 3. Based on the data presented in this table, it becomes clear that increasing different amounts of CR has not significantly affected the EC and pH of both types of soil in this limited period of incubation.

Considering the table, it is uncovered that with expanding the utilization of CR, the electrical conductivity of loamy sand soil has slight expanding pattern while this pattern has been declining in silty clay soil. On the other hand, increasing the amount of CR, increased and decreased the salinity in the loamy sand and silty clay soils, respectively, but as mentioned this slight changes were not statistically significant.

pH changes were quite different in both types of soils so that, by increasing the amount of crumb rubber, loamy sand soil's pH value decreases, whereas silty clay soil's pH was increased.

As previously mentioned, the main feature of CR particles is their low biodegradability and long-term effectiveness in soil. So no statistically significant effect of these treatments on a limited time scale seems quite logical. Due to the abundance of lime in semi-arid soils, (such as Kerman-Iran), overcoming buffering capacity and changing chemical properties of these soils needs more incubation time.

Organic carbon content (OC)

CR is a complex vulcanized elastic which is essentially involved natural rubber (NR), like polyisoprene, and synthetic elastic (SR), like styrene-butadiene elastic as well as butadiene elastic, which are cross connected with sulphur and fortified with carbon dark (CB) (Ghavibazoo and Abdelrahman 2013). Najim and Hall (2012) reported that CR had at least 28 percent of carbon dark by weight. So as

Table 2 Selected physical and chemical properties of the studied soils

Texture	Sand(%)	Silt (%)	Clay (%)	O.C (%)	EC (dS m ⁻¹)	pH (-)	Zn (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Cu (mg kg ⁻¹)	ρ_b (gr cm ⁻³)
Loamy sand	85	4	11	0.0	1.37	7.5	1.33	3.22	0.32	1.64
Silty clay	3	42	55	0.01	1.16	7.9	0.92	4.83	0.84	1.45

expected, the addition of CR significantly increased the organic carbon content (OC) in both soils. Since the soil's organic carbon content is very small in the control sample of both soils, then increase in OC, was highly significant ($p < 0.001$) when the CR amount was increased in two soils (Table 3).

For loamy sand soil, organic carbon content from about zero percent (in control) was increased to 1.4% in the $S_{0.48}$ treatment. While in the silty clay soil due to weaker aeration, organic carbon content in highest CR application rate ($C_{0.48}$), reached to 2.1%.

Considering these results, it can be concluded that in areas where natural organic material is not available, addition of CR particles can be the convenient, inexpensive and a fast solution to improve soil organic carbon content.

Micronutrient availability

The investigation results indicated that using CR as soil modification had significant effect on the soil micronutrient such as Fe and Zn, but at different CR application rate, the copper content is not significantly changed (Table 3).

In the loamy sand substrate, the concentration of zinc increased significantly ($p < 0.001$), when the amount of CR was increased to 0.24 g kg⁻¹ and in higher application values ($S_{0.36}$ and $S_{0.48}$), despite slight increases in zinc content, these changes were not statistically significant. Also in these substrates, the concentration of Fe increased ($p < 0.001$), when the added CR was 0.36 g kg⁻¹ and between $S_{0.36}$ and $S_{0.48}$ treatments, significant changes were not seen (Table 3).

For silty clay soil, increasing the concentration of applied CR has a significant effect on all treatments, so that the Zn content in control treatment (0.91 mg kg⁻¹) has increased up to 17.97 mg kg⁻¹ in $C_{0.48}$ treatment. In the case of Fe for silty clay soil, there was significant difference between the lowest and highest CR application value with control. Increasing Zn content by increasing the CR application rate can be attributed to pure Zn-Oxide which was used in tyre production process. This results demonstrated that these findings are in perfect agreement with Taheri et al. (2011) which said CR and rubber ash were very effective in improving DTPA-extractable Zn in a calcareous Zn-insufficient soil.

Unlike the iron and zinc elements, increasing the application of CR in different amounts had no significant effect on increasing copper content in all treatments. The main reason for this can be attributed that copper unlike iron and zinc, not involved directly in the tires production process.

However, in calcareous soils, such as our research soils, due to the stabilization of metal elements such as zinc in top soil, there are little concerns regarding contamination of these elements, but by reducing the soil's pH and in acidic soils, due to the abundance of zinc in CR, application of this modifier should be used with caution.

Effect of CR amendment on soil physical properties

Bulk density (BD)

The mean comparison results of different CR application rate indicated that the application of CR cause significant decrease of soil bulk density (BD) in both soils.

In loamy sand soil, soil bulk density was decreased significantly ($p < 0.001$) from 1.64 g cm⁻³ in control treatment to 1.40 g cm⁻³ by addition of 0.48 g kg⁻³ CR to the soil and also for silty clay soil, bulk density was reduced significantly ($p < 0.05$) from 1.44 g cm⁻³ in the control to 1.28 g cm⁻³ in the 0.48 g kg⁻³ CR treatment (Table 3). These results are consistent with the findings of Zhao et al. (2011) who said that CR application decreased soil bulk density in a sand-based medium.

Porous structure in tyres causes a significant reduction in both soil bulk densities. This property of CR has potential for usage in environments that have high traffic and have been subjected to density increases.

Mean weight diameter (MWD)

Based on the results presented in Table 3, the application of different amount of CR had significant effect on soil aggregate mean weight diameter (MWD). Duncan's multiple range test was employed for mean comparison of the different CR levels on aggregate MWD (Table 3). Considering mean comparison data in Table 3, the addition of CR significantly increased the MWD in both soils. In loamy sand soil, MWD increased significantly ($p < 0.001$)



Table 3 Substrate's Chemical and physical characteristics based on varying magnitudes of added crumb rubber

	EC (dS m ⁻¹)	pH	O.C %	Zn (mg Kg ⁻¹)	Fe (mg Kg ⁻¹)	Cu (mg Kg ⁻¹)	BD (g cm ⁻³)	MWD (mm)	PR (MPa)	D (-)
S ₀	1.37 ± 5.95 ^a	7.53 ± 5.7 ^a	0 ^c	1.40 ± 1.47 ^c	3.2 ± 0.7 ^c	0.32 ± 1.66 ^a	1.64 ± 0.47 ^a	0.11 ± 1.28 ^c	1.36 ± 6.19 ^a	4.7 ± 1.23 ^a
S _{0.12}	1.57 ± 0.2 ^a	7.52 ± 0.2 ^a	0.40 ^d	6.66 ± 0.06 ^b	4.5 ± 0.43 ^b	0.33 ^a	1.5 ± 0.08 ^{ab}	0.17 ± 0.02 ^b	1.21 ± 2.71 ^{ab}	4.9 ± 0.31 ^a
S _{0.24}	1.53 ± 0.21 ^a	7.41 ± 0.17 ^a	0.8 ± 0.22 ^c	16.21 ± 3.18 ^a	4.7 ± 0.73 ^b	0.31 ± 0.01 ^a	1.5 ± 0.07 ^b	0.17 ± 0.03 ^b	1.22 ± 0.096 ^{ab}	5.0 ± 0.25 ^a
S _{0.36}	1.57 ± 0.19 ^a	7.42 ± 0.18 ^a	1.1 ± 0.36 ^b	16.25 ± 6.58 ^a	5.8 ± 0.85 ^a	0.36 ± 0.02 ^a	1.50 ± 0.07 ^b	0.18 ± 0.03 ^b	1.15 ± 0.1 ^{ab}	4.2 ± 0.23 ^b
S _{0.48}	1.58 ± 0.19 ^a	7.39 ± 0.17 ^a	1.4 ± 0.45 ^a	17.02 ± 6.72 ^a	5.8 ± 1.05 ^a	0.30 ± 0.02 ^a	1.40 ± 0.07 ^c	0.23 ± 0.03 ^a	1.01 ± 0.12 ^b	4.2 ± 0.39 ^b
C ₀	1.07 ± 1.57 ^a	7.9 ± 1.38 ^a	0.01 ^e	0.91 ^c	4.9 ± 0.08 ^c	0.53 ^a	1.44 ± 0.7 ^a	0.14 ^c	3.49 ± 0.73 ^a	4.34 ^a
C _{0.12}	1.01 ± 0.19 ^a	7.9 ± 0.2 ^a	0.58 ^d	16.72 ± 0.43 ^b	6.03 ± 0.46 ^{bc}	0.90 ± 0.09 ^a	1.39 ± 0.02 ^{ab}	0.16 ^c	2.96 ± 0.34 ^b	4.1 ± 0.03 ^a
C _{0.24}	1.01 ± 0.17 ^a	7.96 ± 0.17 ^a	1.2 ± 0.05 ^c	17.20 ± 1.16 ^{ab}	7.0 ± 2.36 ^{abc}	0.83 ± 0.2 ^a	1.3 ± 0.07 ^{abc}	0.22 ^b	2.36 ± 0.39 ^c	3.81 ± 0.1 ^b
C _{0.36}	0.99 ± 0.16 ^a	8.03 ± 0.17 ^a	1.8 ± 0.21 ^b	17.67 ± 0.04 ^{ab}	7.54 ± 1.28 ^{ab}	0.79 ± 0.1 ^a	1.32 ± 0.06 ^{bc}	0.26 ± 0.05 ^b	2.30 ± 0.53 ^{cd}	3.8 ± 0.18 ^b
C _{0.48}	0.88 ± 0.16 ^a	8.11 ± 0.17 ^a	2.1 ± 0.05 ^a	17.97 ± 0.04 ^a	8.74 ± 0.96 ^a	0.88 ± 0.13 ^a	1.28 ± 0.06 ^c	0.34 ± 0.03 ^a	1.94 ± 0.54 ^d	3.5 ± 0.06 ^c

S loamy sand, C silty clay, BD bulk density, MWD mean weight diameter, PR penetration resistance, D fractal dimension

The same letters in each group indicate no significant differences according to Duncan's Multiple Range Tests



from 0.11 mm in control treatment to 0.23 mm at highest CR level ($S_{0.48}$). Also for silty clay soil, MWD was increased significantly ($p < 0.001$) from 0.14 mm in control treatment to 0.34 mm in the 0.48 g kg⁻¹ CR treatment ($C_{0.48}$). These finding is strong evidence that the CR application in soil through its effect on SOC increased MWD significantly. The strong correlation between MWD and SOC were reported by different researchers around the world. Chaney and Shift (1984) revealed a direct relationship between aggregate stability and SOC content in 120 soils gathered from various soil arrangement in Scotland and England. Similarly, Nyamangara et al. (2001) detailed that a 10–38% addition in soil organic carbon with yearly utilization of cows compost at a rate of 12.5 Mg ha⁻¹ for a long time brought about three to fourfold increment in soil MWD in a granitic sandy soil in Zimbabwe.

Fractal dimension (D)

There are many methods to describe the aggregate stability which the important ones include several sieving methods leading to mean weight diameter (MWD), geometric weight diameter (GMD) and in the last few decades fractal dimension index (D). These have been used to describe aggregate stability. In this research, the soil aggregate's fractal dimension was obtained from dry sieving data and using the formulas 3 and 4. The addition of CR significantly decreased ($p < 0.001$) the D in loamy sand soil when the amount of CR was increased up to 0.36 g kg⁻¹, whereas in silty clay substrate, the decrease in the D with increasing rate of amendment was significant ($p < 0.001$) when the CR amount reached to 0.48 g kg⁻¹. As it is clear from these findings, aggregate's fractal dimension (D) has inverse proportionality with mean weight diameter, significantly decreasing the fractal dimension of different treatments related to improving soil structure at various level of CR application.

Penetrometer resistance (PR)

One of the negative effects of the lack of organic matter in arid and semi-arid soils, like Iran, is increasing soil penetration resistance which is caused by weak soil structure.

High penetration resistance in these soils imposes restrictions during soil tillage and plowing, water infiltration into the soil, soil respiration and seed germination. This research revealed that the addition of CR significantly decreased soil penetration resistance in both types of soils.

In loamy sand soil, penetration resistance was decreased from 1.36 MPa in control to 1.01 MPa in $S_{0.48}$ treatment. While this decline rate was higher in silty clay soil, so that the control penetration resistance was 3.49 MPa ,it

decreased significantly to 1.94 MPa in $C_{0.48}$ treatment. These results are consistent with the findings of Groenevelt and Grunthal (1998) who said that an increase of 10–20% of CR fundamentally decreases surface hardness of games turf.

Effect of CR amendment on soil hydraulic properties

One of the most important ways to deal with water shortage in arid and semi-arid regions is adding amendments to soil in order to increase water use efficiency and improve the physical properties of these soils. The non-linear relationship between soil water content (θ_v) and its matric potential (ψ_m) called soil water characteristic curve (SWCC) which expresses the effect of soil structure, total porosity and pore size distribution on soil water availability.

By studying the soil moisture characteristic curve at the difference treatment levels (0.12, 0.24, 0.36 and 0.48 g of crumb rubber/kg soil), it was revealed that by addition of CR application rate, water content increased at each suction point in both types of soils and maximum water content was gained at highest application rate of CR (0.48 g kg⁻¹) (Fig. 1).

Observing the overall considering of SWCC in low suction points (1, 100 and 330 cm) and high suction points (5000–15,000 cm) range, it can be concluded that significant amount of moisture absorbed by the CR particle is released in low suction points, so the release of moisture in low suction point is considered as an advantage for using CR, especially in moderate to heavy textural soils. Comparison of residual water content at high suction points (5000–15,000 cm) showed that the residual water content in the rubber-amended soil was also significant, especially at high levels of CR application. The reasons for the increase of moisture in the treatments containing CR can be attributed to increasing porosity, decreasing density and increasing surface area of rubber-amended soils. In this area, Riggle (1994) expressed that incorporating rubber particles in soil could enhance the water use efficiency by up to 30%. In general, polymers due to their hydrophilic properties are effective in improving soil properties especially in increasing soil moisture content.

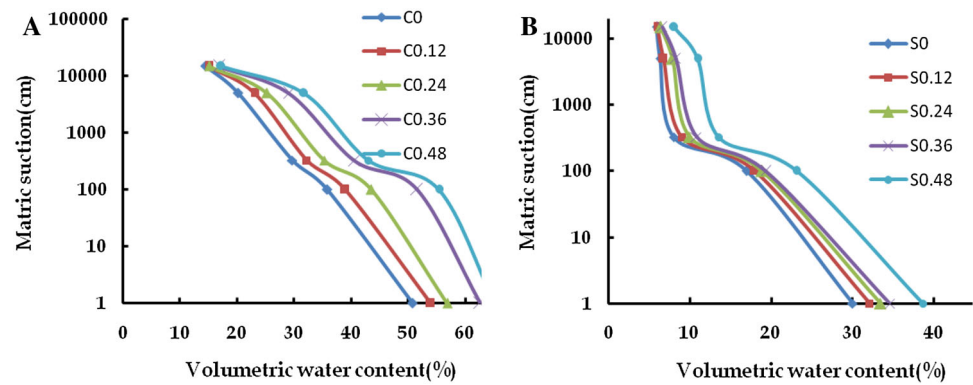
Effect of CR amendment on soil water retention curve parameters

Plant available water content (PAWC)

Routinely, plant-available water content (PAWC) is obtained by subtracting moisture at field capacity and permanent wilting point. Based on the results as given in Table 4, CR particles significantly ($p < 0.001$) increased



Fig. 1 Soil retention curves of silty clay (a) and loamy sand (b) soils as affected by different CR level



the PAWC in both types of soil, but the amount of PAWC increment in silty clay soil was greater than this increment in loamy sand soil, so that PAWC enhanced from 15.1% in C_0 (as control treatment of silty clay soil) to 25.7% in highest CR application rate ($C_{0.48}$), and this means an increase of more than 10 percent of PAWC compared to the control. In terms of availability of soil water for plants, adding CR particles in clay soils with very fine pores leads to the improvement of the availability of soil water for plants. For loamy sand soil, the maximum amount of PAWC is related to $S_{0.48}$ treatment and it was 5.45% and a difference with the control (S_0) is measured about 3%. These results confirmed that the CR addition in soil could improve pore size distribution and helped to increase the plant-available water content.

Relative water capacity (RWC)

Another indicator that shows the status of availability of soil water for plants is relative water capacity (RWC) index. Relative water capacity is obtained from the ratio of

soil moisture at field capacity to soil saturation water content. These results indicated that CR affects the RWC in both soils significantly (Table 4).

Air capacity (AC)

The plant root needs both air and water simultaneously to survive. That portion of the soil porosity which is occupied by air is called the air capacity (AC). So soil air capacity index is one of the important indices for plant growth and its survival.

The volumetric difference between field capacity (θ_{fc}) and water saturated point (θ_s) considered as soil air capacity which both of these parameters (e.g. θ_{fc} and θ_s) are acquired from soil moisture characteristics curve. Based on statistical analysis, increasing the amount of CR in the loamy sand substrates significantly ($p < 0.05$) increased air capacity, while it did not have any effect on silty clay soil (Table 4).

Table 4 Different soil water retention curve indices based on varying magnitudes of added crumb rubber

Treatment	PAWC(%)	AC(%)	RWC (%)
S_0	2.08 ± 7.02^d	21.96 ± 5.65^b	0.26 ± 7.17^c
$S_{0.12}$	2.99 ± 0.5^c	23.02 ± 1^b	0.28 ± 0.02^{bc}
$S_{0.24}$	3.50 ± 0.67^{bc}	23.45 ± 1.06^{ab}	0.29 ± 0.01^{bc}
$S_{0.36}$	4.18 ± 0.75^b	23.71 ± 1.09^{ab}	0.31 ± 0.02^b
$S_{0.48}$	5.45 ± 0.9^a	25.07 ± 1.1^a	0.35 ± 0.02^a
C_0	15.15 ± 7.16^e	21.16 ± 2.93^a	0.58 ± 7.53^c
$C_{0.12}$	17.12 ± 1^d	21.83 ± 2^a	0.59 ± 0.02^c
$C_{0.24}$	20.13 ± 1.39^c	21.65 ± 1.82^a	0.61 ± 0.01^{bc}
$C_{0.36}$	23.62 ± 2.33^b	22.16 ± 1.75^a	0.64 ± 0.02^{ab}
$C_{0.48}$	25.74 ± 3.44^a	22.26 ± 1.74^a	0.65 ± 0.03^a

AWC available water content, AC air capacity, RWC relative water content

The same letters in each group indicate no significant differences according to Duncan's Multiple Range Tests

Conclusion

Soil organic matter is considered as the main factor of soil quality. Soil organic matter deficit is the most common problem in arid and semi-arid soils. In this study, amending two soils with distinct texture with different rates of crumb rubber modified some hydro-physical and chemical properties of soils.

Our results indicated that the application of CR has significant effect on decreasing the amount of soil compaction index (based on decreasing of bulk density and penetration resistance) and increasing volumetric water content at different suction points so that adding crumb rubber modified the water retention curve coefficients. Increasing plant-available water content (especially in silty clay soil) and soil relative water content are the examples of the positive impact of the crumb rubber application as a modifier.



According to different studies, the micronutrient deficits are very common in calcareous soils of arid and semi-arid regions like Iran. The results of this study showed that the addition of crumb rubber can be a good source of microelements, especially for zinc.

In general, the results of this research proved positive impact of crumb rubber particles on various soil properties. Since this research was carried out in controlled greenhouse conditions and for limited incubation time, it is recommended that the effect of adding crumb rubber particles be evaluated in field condition and for longer times.

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