Using Shear Strength Parameters to Predict Erosion Resistance of Soils Treated by Chitosan

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Abstract

The world population is growing and the need for water and food is increasing. Dams are considered as one of the main sources of drinking, agricultural and industrial water sources. On the other hand, agricultural land is the main source of food. However, dam reservoirs and fertile lands as the main food resources are threatened by soil erosion. Different methods of soil improvements are therefore, used to mitigate or control soil erosion. Recently use of environmentally friendly methods such as Microbial Induced Calcite Precipitation (MICP), Enzyme Induced Calcium carbonate Precipitation (EICP) and mixing soil with biopolymers such as Chitosan have attracted researcher's attention in this regard. Soil resistance to erosion can be determined using laboratory or field tests such as flume tests, jet erosion tests, rotating cylinder tests, soil dispersion tests, and hole or crack tests. These tests, however, are costly and time consuming. Indirect estimation of soil erodibility parameters can replace these costly methods and overcome this problem. In this paper, the shear strength parameters of soil samples treated using MICP, EICP and Chitosan are used to predict soil erosion potential. It is found that by using soil-improving methods cited, the soil erosion resistance increases significantly. An empirical relation between soil critical shear stress and shear strength is proposed and verified.

Keywords: soil erosion, shear strength, critical shear stress, suspension index.

1. INTRODUCTION

Erosion is defined as transportation of soil particles from one location and its deposition in another place, by wind, water or other factors. Soil erosion by water is in fact one of the typical geological phenomena which changes the earth landscapes. In the erosion process, two different operations are performed: the separation of particles and their transportation and displacement. Factors such as topography, the amount and severity of rainfall and wind speed, freezing and intermittent melting, water flow and raindrops have significant effects on soil erosion and cause soil particles washing. Scouring of soils due to water erosion leads to instability of earth slopes, foundations, embankments and roads, for example, crucial for civil and environmental projects. The scouring of surface soils also causes the loss of fertile soil, which is used to produce food. Every year 75 billion tons of fertile soil are eroded away worldwide, causing a financial loss of ~US$400 billion per year (GSP, 2017). Borrelli, et al. (2017) predict a potential overall increase in global soil erosion due to cropland expansion with the greatest increase for Sub-Saharan Africa, South America and Southeast Asia. The highest estimates of soil erosion rates has been found for least developed economies.

Among the physical properties of soils affected by erosion, the most important is soil structural stability. The soil structural stability is influenced mostly by physical and chemical properties of soil. Soil structural stability depends on factors such as texture, clay content, size and shape of particles. The higher structural stability of the soil particles leads in less erosion. However, it produces a large amount of runoff water. Soil particles separation and therefore soil structural instability, is strongly related to the cohesion and shear strength of the soil. Soil improvement methods have therefore been developed to increase the soil resistance to erosion. Zuazo and Pleguezuelo (2008), categorized soil erosion mitigation methods into three groups: biological, mechanical and chemical methods. Mechanical erosion control methods includes construction of traps and sediment gullies in the areas of generation and sediment transport. The containment system embedded in these methods allows the movement of particles from its source, but after the initial movement, it tries to stabilize and separate the particles. Geosynthetic materials such as geogrids are also used to protect the soil against erosion as a mechanical measure. These materials can be manufactured from natural or synthetic substances to reduce the cost. However, the environmental impact of synthetic materials and the durability of natural materials is always a great concern (Bell, 2004).

Another group of conventional erosion control methods includes surface soil stabilization methods using chemicals. Although chemical materials have reasonable prices, durability and acceptable efficiency and are easy to use, they suffer from many side effects that cannot be ignored. Most of these chemicals if not all, are toxic and may contaminate the soil and the ground water and change the soil pH (Orts and Glenn, 1999; Kabanov, 2003).

With the advancement of technology, modern methods have been developed to solve geotechnical problems, including soil erosion. When geotechnical engineers were looking for environmentally friendly methods or "green" methods to improve soil properties, they realized that soil is in fact a "living ecosystem" in which biological and beneficial chemical processes are ongoing. Treatment of soils using these substances lies within the scope of bio-geotechnics, which is a new subfield of geotechnical engineering.

Microorganisms such as algae, fungus and bacteria can be used to control soil erosion. With this technique, known as microbial induced calcite precipitation (MICP), the general mechanism of preventing erosion by microorganisms involves the production of materials by these organisms, which, by attaching soil particles together, causes the soil to withstand higher water-induced shear stresses (Whiffin et al., 2007). Wiffin et al. (2007) reported significant improvement to soil strength and stiffness of soil samples treated by MICP. However, the use of MICP in practice is very laborious and time consuming. In contrast, the new environmentally friendly biological products such as enzymes and biopolymers can be used. Soil improvement via enzyme induced carbonate precipitation (EICP) is a bio-geotechnical ground improvement method in which calcium carbonate is used to fill soil pores by an aqueous solution (Hamdan et al. 2013; Kavazanjian and Hamdan, 2015; Oliveira et al. 2016). Biopolymers are in fact polymers that are synthesized using biological organisms and include monomeric units that interconnect and make larger shapes. It has been shown that direct use of enzyme and biopolymers in soil has several advantages over the MICP. Urease enzyme is often used in EICP (Oliveira et al., 2016; Almajed et al., 2018). More recently, biopolymers such as Chitosan, xanthan, guar, carrageenan, and starches have been used as additives to improve soil strength and stability, which in turn improves the soil resistance to water and wind erosion (Orts et al., 1999, 2000). The effect of biopolymer on mechanical and physical behavior of treated soil differs according to the chemical composition of biopolymer. Among many biopolymers used for soil improvement, Chitosan is considered by geotechnical and geoenvironmental engineers as an effective material to reduce soil erosion by wind and water. Chitosan is a low cost biopolymer obtained mostly from discarded crustacean shells of food industry. The results of wind tunnel tests have also shown that Chitosan is also successful in preventing the wind soil erosion (Alsanad, 2011; Kavazanjian et al., 2009; Kumar, 2000; Orts et al., 1999, 2000; Aguilar et al., 2016). Aguilar et al., 2016 using water drip test results showed that coating of soil surface with low concentration Chitosan solutions was sufficient to provide protection against water drip erosion. As a result, Chitosan offers great potential for several geoenvironmental applications.

The soil erosion resistance can be determined using laboratory or field tests such as flume tests, jet erosion tests (JET), rotating cylinder tests, soil dispersion tests, hole or crack tests, and erosion function apparatus (Wan and Fell, 2004). These tests however are expensive and needs special facilities. They are also time consuming. The indirect estimation of soil erodibility parameters can therefore be used to predict soil resistance to erosion. Soil shear strength is among the most influential parameters on soil erosion. Shear strength of soils can be determined using basic soil tests such as triaxial, uniaxial and direct shear tests. These tests can be easily performed and shear strength parameters can be determined. In this paper, the relation between soil erosion potential and shear strength is used to estimate soil erodibility parameters of both natural and biotechnical treated soils.

2. SOIL ERODIBILITY PARAMETERS

Although experimental and field testing are the most reliable methods to predict soil erosion resistance but due to the cost and complexity of the experiments in many ways and roles of many interdependent parameters it is hardly used to elucidate soil erosion resistance in practice. The analytical and numerical methods are easier to perform but not as reliable as the experimental methods and can only be used when verified by experimental results. Empirical methods on the other hand since are related to experimental studies results may be a more reliable approach to this problem compared to numerical methods. This is because they use the reliability of experimental methods while avoid the complexity of the laboratory or field tests. In the following section common physical and mechanical properties of soils have been used to estimate the parameters related to soil erosion, mainly critical shear stress and soil suspension index. These parameters have then been used to predict the untreated and treated soil resistance to erosion.

2.1. SOIL SHEAR STRENGTH

Soil shear strength (τf) has been found to influence the soil erodibility (Paterson, 1997; Watts et al., 2003). Using the Mohr-Coulomb failure criteria, the soil shear strength can be calculated by eq. (1) (Nadai, 1950).

$$\tau_f = c + \sigma_n \tan\varphi \qquad (1)$$

where $\tau_f$is the shear strength along the shear failure plane (kPa), c is the cohesion (kPa), σn is the applied normal stress to the shear plane (kPa), and φ is the soil internal friction angle. Cohesion and internal friction angle for any soil can be determined by conducting direct shear or triaxial tests on soil samples. σn is due to soil mass and external loads above the failure plane. Close to ground surface, both mass of soil and external forces are negligible. Therefore, if the matric or capillary potential, which is attributed to the adhesion of water molecules to soil particles is neglected, the strength of soil is solely a function of the soil cohesion.

2.2. CRITICAL SHEAR STRESS

Raindrop-impact forces causes shear failure when shear stresses developed in a shear plane exceeds the soil shear strength. Detachment of soil particles occurs and soil erosion initiates. Therefore, it is obvious that soils with higher shear strength are more resistant to soil erosion. Critical shear stress (τ_{crt}) is defined as the stress if exceeded soil erosion initiates (Teisson et al. 1993). Although some researchers performed in situ determination of critical shear stress measurement, others tried to correlate the critical shear stress of soils to geotechnical shear strength which can be determined more easily (Paterson, 1997; Watts et al., 2003).

Watts et al., 2003, for instance studied the correlation between soil shear strength and critical shear stress and proposed equation (2) relating these two parameters:

$$\tau_{crt} = 2.145 + 0.520 \ln(\tau_f) \quad \text{(Pa)} \qquad (2)$$

This parameter is a quantitative index of soil erosion resistance but its direct measurement is costly and time consuming.

2.3. SOIL SUSPENSION INDEX

Tolhurst et al. (1999) used the slope of the erosion profile as a relative, semi-quantitative measure of the erosion rate, the suspension index (Si). It represents the particle flux in relation to increasing erosion shear stress. A high value of Si is therefore indicative of rapid erosion, whilst a less value shows more gradual erosion. Watts et al., 2003 have presented a relationship between the suspension index, Si, indicating the erosion rate and the soil shear strength as:

$$Si = 3.062 - 0.620 \ln(\tau_f) \qquad (3)$$

Equations 2 and 3 imply that any factor changing the soil shear strength leads into change of soil erosion resistance. It is therefore anticipated that whether the increase in soil shear strength arise due to the inherent mechanical properties or due to treatment of soil it will reduce the soil erodibility. In the past, different techniques of controlling and reducing soil erosion have been developed and used.

3. SOIL ERODIBILITY PARAMETERS

A clay soil, classified as low plastic clay (CL) in accordance to the Unified Soil Classification System (USCS) has been used to perform a series of experiments at the Geotechnical Laboratories of the Department of Civil and Environmental Engineering, Shiraz University (Ghadir, 2017). The Atterberg's plastic and liquid limits of the soil were 22 and 31, respectively.

Chitosan used for soil treatment was extracted from shrimp shell wastes. To prepare treated soil samples either water or Chitosan solution was manually added to soil and mixed for 5 min. The concentrations of the Chitosan relative to the mass of the dry soil were 0.00, 0.02, 0.04, 0.08, and 0.16% (Ghadir 2017).

To measure the shear strength of treated and untreated soil, direct shear tests on 100 × 100 × 27 mm samples exposed to 50, 100 and 150 kPa vertical confinements were conducted. A pneumatic actuator was used until the vertical strain stabilized before subjecting the samples to the horizontal shear force. The samples were sheared under a saturated and unsaturated condition (Ghadir 2017). Test results of saturated conditions were used here to simulate the field condition of the soil subjected to water erosion.

4. RESULTS AND DISCUSSIONS

Shear stress-horizontal displacement curves and peak shear strengths of the Chitosan treated clay specimens are used to determine the mechanical parameters of the treated soil. The shear strengths parameters obtained for untreated and treated samples are illustrated in Table 1 (Ghadir 2017). As it can be seen from Table 1, cohesion of soil treated with Chitosan increased up to three times compared to untreated sample. Friction angle, φ, for untreated soil was 21.8 degrees and that for treated soil with 16% chitosan concentration was 22.3 degrees. This indicates that the friction angles for both treated and untreated specimens were almost similar (Ghadir 2017).

Fig. 1 shows the change in critical shear stress versus Chitosan concentration. It can be seen from this figure that increasing the concentration of Chitosan leads to increase in soil critical shear stress and therefore increases the soil resistance to erosion. However, the rate of increase decreases after reaching a threshold value of 0.1% Chitosan by weight. Increasing the Chitosan concentration further has no significant effect on soil resistance to erosion.

The process of curve fitting is used to correlate the changes in critical shear stress of soil tested as a function of Chitosan concentration (%). This relation as shown in figure 1 has the following form:

τ_(crt t)= A B^c (4)

wehre B is the Chitosan concentration in soil mix in percent and A and c are constants. The values of A and c are 4.10 and 0.03 respectively for the Chitosan treated soil used in this study. The coefficient of variation, R2 is 0.96, which is acceptable. Using this equation, it is possible to predict the improvement of treated soil critical shear stress for any Chitosan concentration.

Table 1. The effect of soil treatment on erosion resistance

Soil sample	Chitosan concentration wt. (%)*	Cohesion C (kPa)*	Critical shear stress, τ_{crt}(Pa)	CSSR (%)	Suspension index, Si	Improvement in Si (%)
Untreated	0.00	10.3	3.36	100	1.62	100
Treated	0.02	15.7	3.58	107	1.35	84
Treated	0.04	20.7	3.72	111	1.18	73
Treated	0.08	24.3	3.80	113	1.08	67
Treated	0.16	30.3	3.92	117	0.95	59

*** Ghadir (2017)**

To compare soil erodibility with that for treated and untreated soil, the value of critical shear stress of treated soil was normalized with respect to that of untreated soil. The critical shear stress ratio (CSSR) is defined as the ratio of treated soil critical shear stress (τcrt t) to untreated soil critical shear stress (τcrt u):

CSSR (%)= τ_(crt t)/(τ_(crt u))*100 (5)

With the treatment of soil, using Chitosan up to 17% increase in soil erodibility resistance is achieved (CSSR, Table 1).

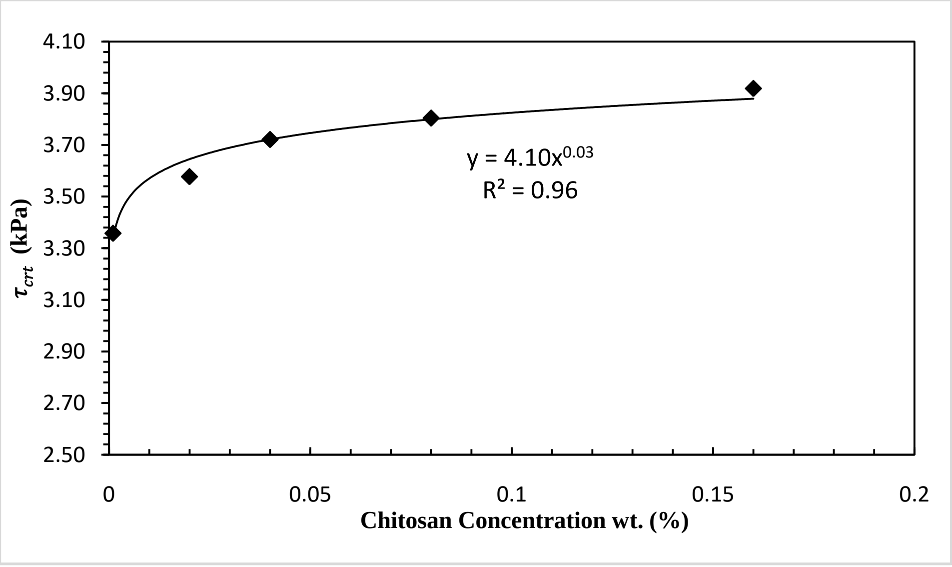

Fig. 1. Change in critical shear stress vs. Chitosan concentration

The values of the suspension index improvement, illustrated in Table 1 and Fig. 2 reveal that Chitosan has caused the decrease in Si as much as 60% (i.e. rate of erosion decreases for treated soil). The rate of change however decreases with increase in Chitosan concentration. This implies that a threshold value of concentration exists in soil improvement, again ~0.10% for this study. By curve fitting process the trend of Si changes with respect to Chitosan concentration can be formulated using a polynomial equation as follows:

$$S_i = Ex^2 + Fx + G \qquad (6)$$

where x is Chitosan concentration and E, F and G are constants and equal to 2303.70, -606.1 and 97.24, respectively for the Chitosan treated soil samples. The coefficient of variation is 0.96.

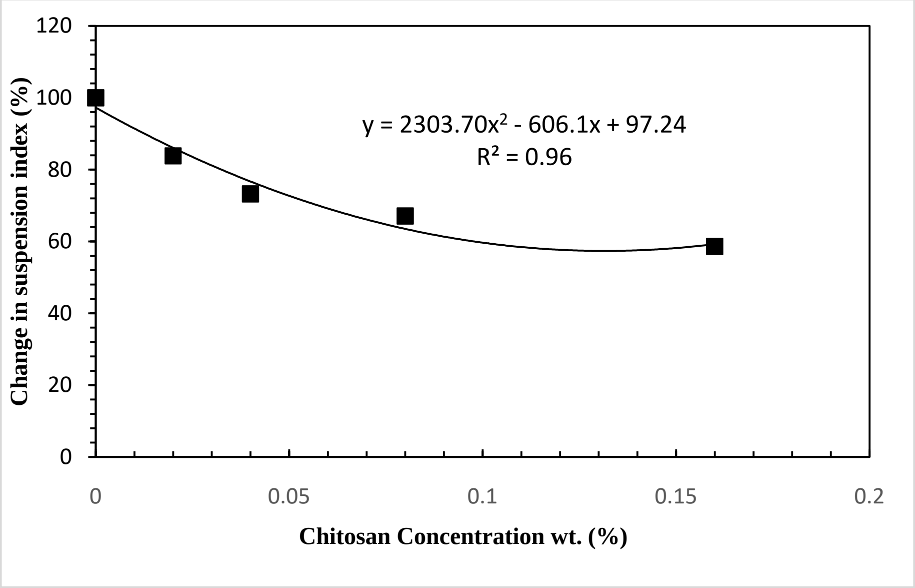

Fig. 2. Variation of relative suspension index vs. Chitosan concentration (%)

4.1. Validation of proposed empirical relations

To validate the relations proposed for treated soils (equations 4) the results reported by Almajed et al.(2018) and Wiffin et al. (2007) have been used. The results of the unconfined compressive strength tests of the treated specimens by EICP method versus the mass percentage of precipitation (i.e. mass of precipitates to initial mass of dry sand, CaCO3 (%)) reported by Almajed et al. (2018) were used to calculate the critical shear stresses and illustrated in Fig. 3. As illustrated in this figure, the critical shear stresses increases with increase in the calcium carbonate concentration. The increase in critical shear stress means increase of the soil resistance to erosion. However the increase rate is decreasing toward a threshold value, for this case ~4% of calcium carbonate. The change in critical shear stress again obeys the power law as in equation 4, with the values of A and c equal to 4.10 and 0.20 respectively. R2 value is 0.94 which is acceptable. This observation is consistent with the findings for soil treated with Chitosan.

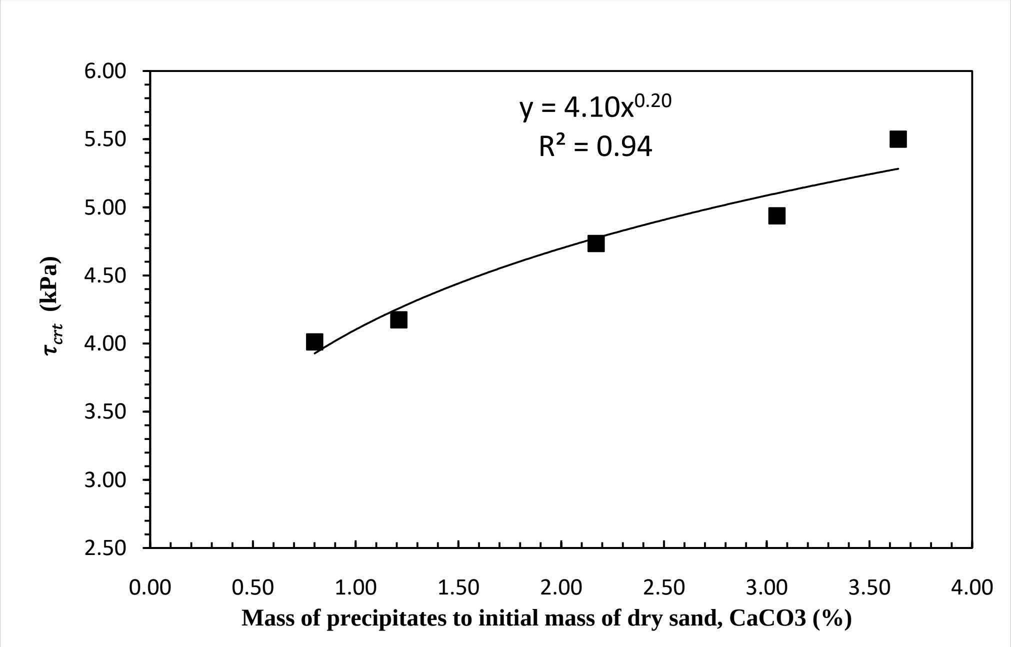

Fig. 3. Change in critical shear stress vs. calcium carbonate precipitation (Almajed et al., 2018)

Wiffin et al. (2007) reported the compressive strengths of treated soil samples by MICP method using single-stage confined drained triaxial tests with a confining pressure of 50 kPa. Having calculated the critical shear stress changes versus mass of precipitation, the same trend of increasing erodibility of treated soil can be seen, Fig. 4.

It can be seen that the empirical equation (i.e. equation 4) proposed for the treatment methods cited earlier is applicable to these data, too. The values of A, c and R2 are 4.08, 0.17 and 0.94, respectively.

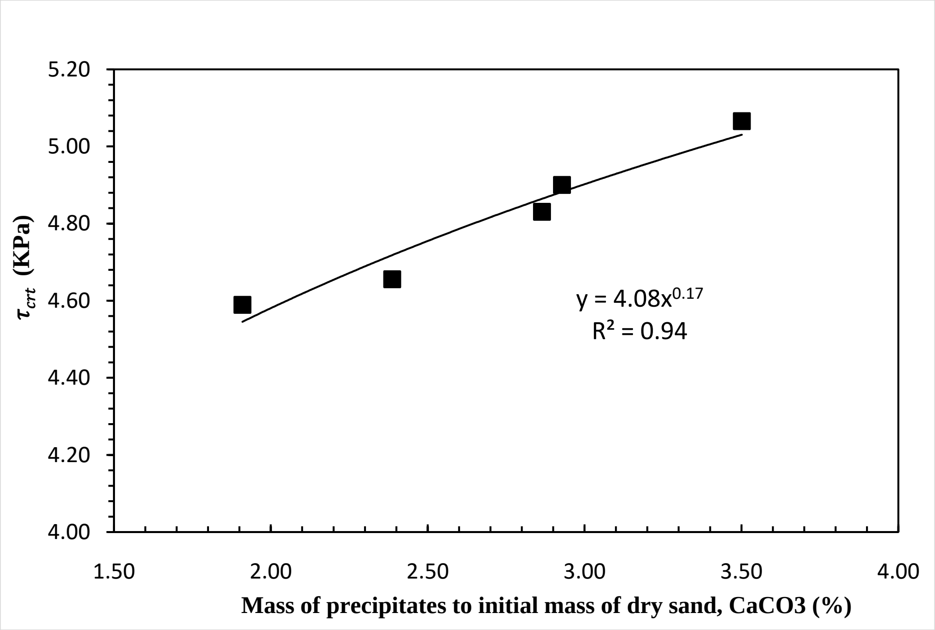

Fig. 4. Change in critical shear stress vs. carbonate precipitation (Wiffin et al., 2007)

Fatehi et al. (2018) introduced Casein and sodium caseinate salt biopolymers as new soil additives to improve the geotechnical behavior of poor graded sand. Mechanical properties of biopolymer treated sand were investigated through a series of unconfined compression laboratory tests. The results have been used to calculate and plot the critical shear stress versus biopolymer concentration, Fig. 5. Again the empirical equation (i.e. equation 4) is applicable to these data. The values of A, c and R2 for casein are 5.13, 0.05 and 0.99, respectively. For sodium caseinate, values of A, c and R2 for casein are 5.16, 0.06 and 0.98, respectively.

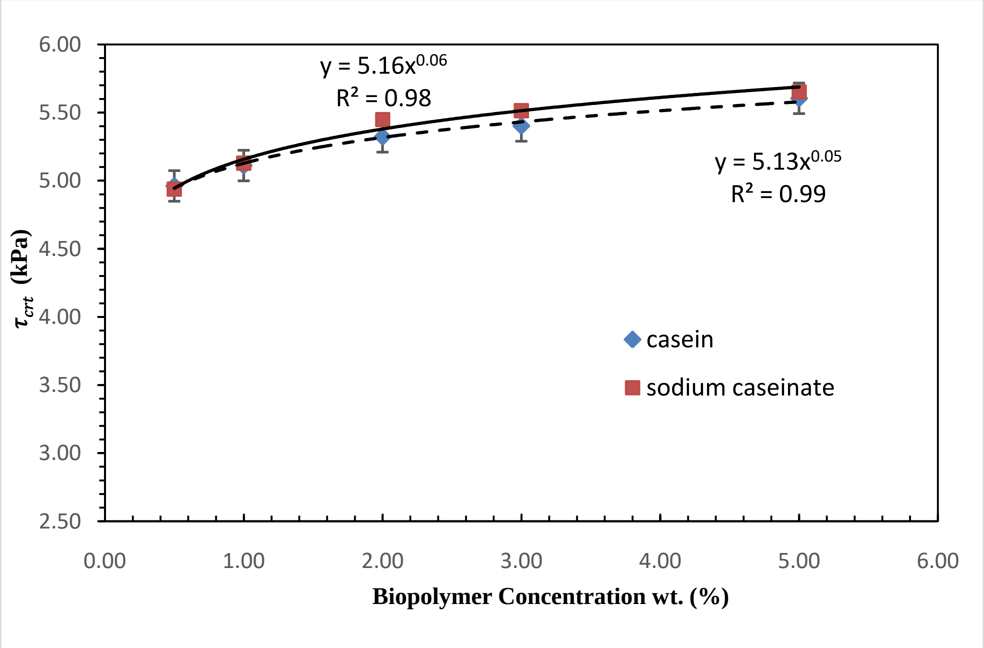

Fig. 5. Change in critical shear stress vs. biopolymer concentration (Fatehi et al., 2018)

5. CONCLUSIONS

The concept of the critical shear stress has been used to predict the change in soil resistance against erosion of Chitosan treated and untreated soils. It was shown that the cohesion of treated soil increased compared to untreated soil. Increasing the shear strength leads to increase in soil critical shear stress and therefore increases the soil resistance to erosion. However the increase rate was found decreasing after a threshold value of additive concentration. An empirical relationship is proposed to predict the treated soil critical shear stress. The critical shear stress ratio (CSSR) as the ratio of treated soil critical shear stress to untreated soil critical shear stress was introduced to show the treated soil erodibility improvement, quantitatively. The proposed relation was validated using the critical shear stresses calculated for EICP and MICP treated soils.

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