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Mechanical Properties of Soft Clay Soil Reinforced by Carbon Fibers

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Abstract One of the problematic soils that frequently causes many problems to the structures is soft clay, due to its low shear strength and high compressibility. This paper examined the effect of the addition of randomly distributed carbon fibers (CF) on the mechanical properties of soft clay soil. Reinforced clay samples consist of fibers randomly mixed with dry clay with different percentages of carbon fibers and the addition of the optimum water content to conduct tests on them. Carbon fibers were added at (0.2%, 0.4%, 0.6%, 0.8%, and 1%) of the dry weight of the soil. Laboratory tests were performed on Carbon fiber-reinforced soil samples, including consistency limits, unconfined compression tests, compaction tests, and direct shear tests. The results indicated an improvement in the mechanical properties of the soft clay soil, where the unconfined compressive strength and soil cohesion increased by 105.99% and 70.73 %, respectively, compared to the unreinforced soil. The results also showed that the optimum fiber content that gives the highest strength is (0.6%).

Keywords: Carbon fibers, Reinforced soils, Soft clay soils, Shear strength, Unconfined compressive strength.

1 Introduction

In geotechnical engineering, the soil reinforcement is widely used to reinforce roadbeds, repair shallow slope failures, and enhance landfill cover behavior. In the past, soft soils were frequently treated with lime, bitumen, cement, chemicals, and recycled materials to enhance their mechanical performance. These additives, however, are not thought to be long-lasting or environmentally friendly. Soil is reinforced by incorporating it with various reinforcing materials to increase its strength and stability, including geotechnical grilles and geotextiles **[1]**. Numerous studies on fiber-reinforced soils have been undertaken because the friction between soil and fiber can improve the soil's mechanical properties **[2]–[4]**. CFs are superior to more common fibers in terms of elastic modulus and tensile strength, such as polypropylene fibers. Soil reinforcement is a good application because of its slow biodegradation rate and exceptional durability **[5]**. CFs have recently attracted increased interest in the field of civil engineering due to their remarkable performance in terms of strength, relatively high aspect ratio, and strong inherent resistance to deterioration. However, the vast majority of published research has focused on incorporating carbon fiber into composites made of cement or concrete. Few studies even touch on how carbon fiber can be used for good soil improvement. Hongzhi Cui et al. **[6]** stated that randomly distributed short carbon fibers can be used as reinforcement for non-cohesive soil. Ranjan et al. **[7]** finer soil particles can develop greater bond strength with fibers due to a lower probability of slip failure than coarser soil particles. As a result, clay soil is expected to achieve high bond strength with carbon fiber. The bearing capacity of the fiber-reinforced soil rose as its relative density increased Additionally, fibers may improve the soil's ductility and resistance to liquefaction **[8]**, **[9]**.

CF is regarded as more effective than polypropylene fiber since a small content of CF can result in significant improvement of soil properties **[6]**. The total cost is reasonable in light of the lower dose requirements for soil stabilization. In addition, as production technology improves, carbon fiber costs are anticipated to decrease.

The purpose of this study is to find out the effect of carbon fibers on the mechanical properties of soft clay

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soils. A series of laboratory tests was conducted on samples of soft clay soils reinforced with carbon fibers, including consistency limits tests, unconfined compression tests, compaction tests, and direct shear tests. The peak strength, shear failure pattern, and stress-strain relationship were examined.

2 Experimental work and material according to ASTM

The primary objective of this study is to assess the reinforcing effects of varying CF contents on the mechanical characteristics of soft clay soil. In this study, a group of tests was administered, which can be categorized as follows:-

1) Consistency limits, compaction, direct shear, and unconfined compression tests were conducted on unreinforced soil samples as control samples under normal stress of 50, 100, and 200 kPa.

2) Soil samples reinforced with various amounts of carbon fibers (0.2%, 0.4%, 0.6%, 0.8%, and 1%) of the dry weight of the soil and a length of 10 mm were subjected to unconfined compression and plasticity index tests.

3) Direct shear tests and compaction were conducted at normal pressures of 50, 100, and 200 kPa on soil samples strengthened with the optimal carbon fiber content of 0.6% of the dry weight of the soil, as determined by unconfined compression experiments.

The carbon fiber shown in **Fig. 1** is a reinforcing material supplied by Sika Egypt. **Table 1** summarizes the mechanical characteristics of CF.

Fig.1 Carbon fiber used in this research.

Table 1 Characteristics of carbon fibers **[10]**.

Characteristics	
Material	100 % carbon
Acid and salt resistance	High
Density	2.267 gm/cm^3
Fiber length	10 mm
Thermal conductivity	Low
Elongation %	1.5
Electrical conductivity	Low
Absorption	Nil
Ultimate Tensile strength, (GPa)	2.80
Elastic Modulus, (GPa)	177

2.1 Soil properties

Soft clay soil samples used for experimental programs in this research were collected from dredging the bottom of Alrmadey canal, which is a tributary of the Nile River passing through Esna city, Luxor. The mechanical properties of the soft clay soil samples are shown in **Table 2**. **Fig. 2** shows the particle size distribution of used soft clay soil. **Fig. 3** shows the compaction curve for natural soil. The curve reveals that the optimum water content is 14.80%, whereas the maximum dry unit weight is 1.62 gm/cm^3.

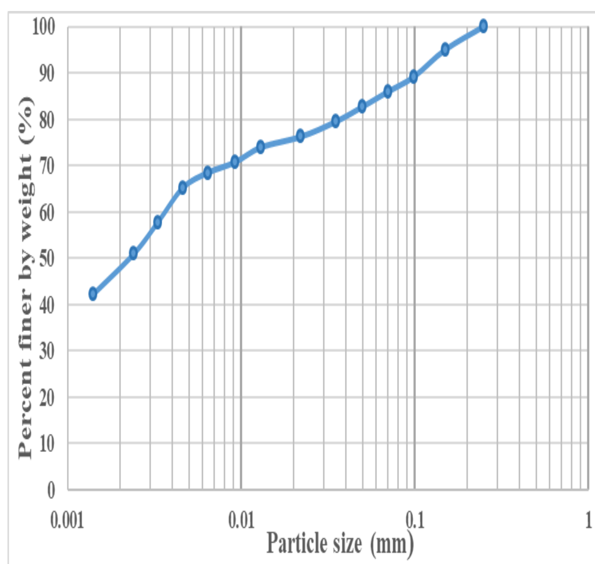


Fig. 2 Particle size distribution of used soft clay soil.

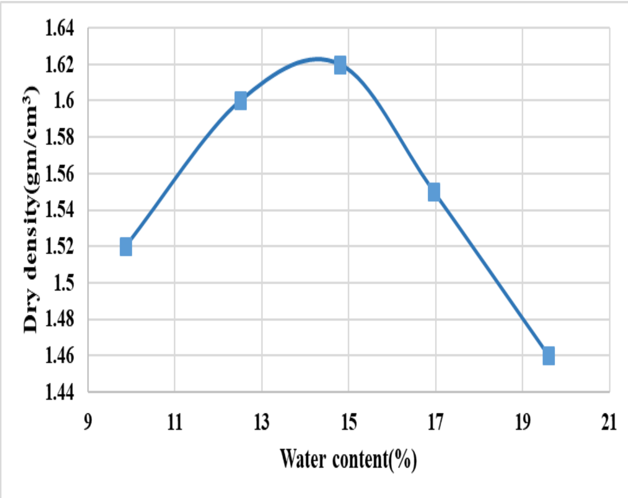


Fig.3 The compaction curve for natural soil.

Table 2 Natural soil samples' mechanical characteristics.

Properties	Value
Maximum dry density	1.62 gm/cm^3
Specific gravity	2.71
Optimum moisture content	14.80 %
Plastic limit	24.28 %
Plasticity index	33.48 %
Liquid limit	57.76 %

2.2 Preparing samples

Samples can be prepared with their natural water contents by determining the moisture content in the laboratory or on-site. Nonetheless, fibers have a tough time spreading out uniformly because of the naturally low water content of the soil. The following method for sample preparation was implemented as a result. The CF was diluted in deionized water before being added to the dry soil. The CF was accurately blended into the soil to ensure uniform distribution. The mixture was then dried for 24 hours at 105° C. Finally, the mixture was ground into a powder, combined with the amount of deionized water desired, and put in a sealed plastic bag for 24 hours. Unconfined compression tests were conducted at the optimum water content to obtain the optimum fiber content, using samples that were 10 cm in height and 5 cm in diameter **[11]**. Direct shear tests were carried out using a metal box with a size of 6 cm x 6 cm and a net thickness of 2 cm, and Soil samples were added at the optimum water content and the test was performed.

2.3 Experimental approaches

In this investigation, consistency limit tests, compaction tests, unconfined compression tests, and direct shear tests were conducted to determine the mechanical properties of non-reinforced and reinforced soft clay soils. During the loading process, the shear rate of the direct shear test was 1.05 mm/min **[12]**, the relationship between shear stress and displacement was continually recorded, and the shear coefficients of the soil (cohesion coefficient and internal friction angle) were determined. Soil samples were subjected to unconfined compression tests at a rate of 1.25 mm/min **[11]** until shear failure. Stress-strain values were continually recorded until the end of the test.

3 Results and discussion

3.1 Consistency limits

The soil's liquid limit (LL), plastic limit (PL), and plasticity index (PI) can all be altered by incorporating fibers. It was found that carbon fibers slightly increase the soil's LL and PL. when CF was added, the plasticity index decreased as shown in **Fig. 4**. The plasticity of the soil generally decreases as a result of the addition of fibers because they make the soil less workable and less compressible. The results are similar to some previous studies using CF **[13]**.

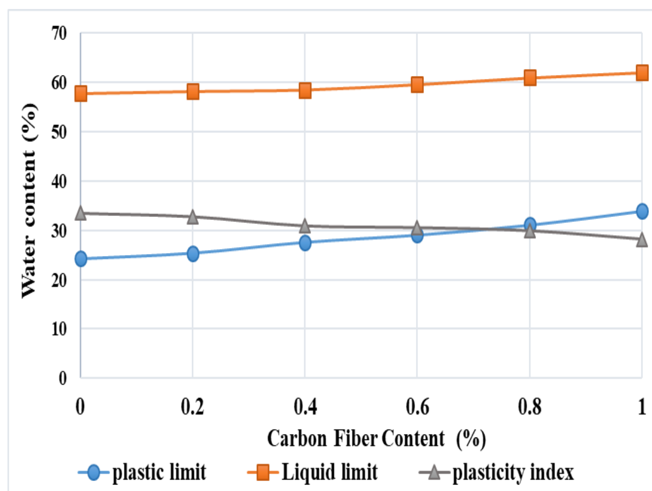


Fig .4 Effect of carbon fiber reinforcement on consistency limits.

3.2. Unconfined compression strength

The relationships between axial strain and unconfined shear strength for soil samples reinforced with various amounts of CF are shown in **Fig. 5**.

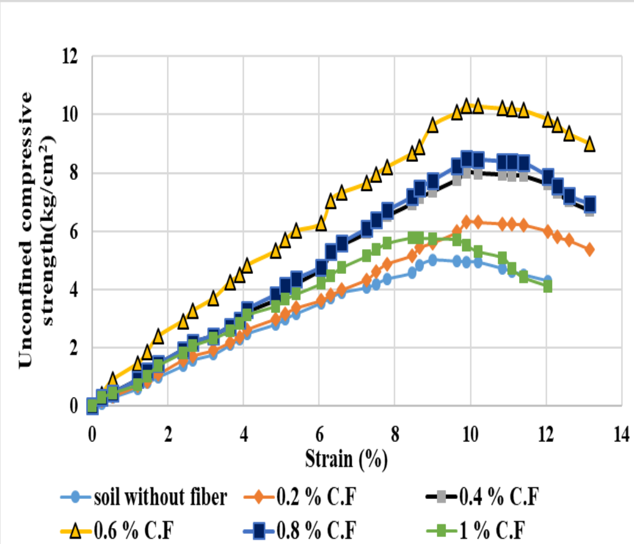


Fig 5. The relation between axial strain and unconfined shear stress for samples of soil reinforced with carbon fibers.

The stress-strain curves demonstrate that the addition of CF increased the maximum shear strength and the post-peak residual strength. In addition, the CF increased specimen rigidity before the peak. The stress-strain curves of samples containing various concentrations of CF with a length of 10 mm exhibited a rapid hardening trend up to the peak, which after that diminished. The maximum compressive strength of soil increases with increasing fiber content until it reaches its maximum value at 0.6% CF, after which it declines with increasing fiber content. The peak shear strength of soil samples containing CF was greater than that of non-reinforced soil samples, whose peak shear strength was 5.01 kg/cm^2, as depicted in **Fig. 6**. The maximum compressive strength increases by 26.35 %, 60.28%, 105.99%, 69.46%, and 15.37%, respectively. The reason for the loss of strength when adding a carbon fiber content greater than 0.6% is that it is difficult to distribute carbon fibers within the soil sample, which results in the formation of clusters of fibers that cause loss of strength. The maximum compressive strength of CF- reinforced soil samples at various ratios and ideal moisture concentrations are shown in **Table 3**. It has been shown from the test results that the optimal content of carbon fiber is 0.6%, which is the content that will be added to conduct the tests.

Table 3 Improve the maximum compressive strength of soil samples.

Fibers %	Max. compressive strength (kg/cm^2)	increase %
0	5.01	0
0.2	6.33	26.35
0.4	8.03	60.28
0.6	10.32	105.99
0.8	8.49	69.46
1.0	5.78	15.37

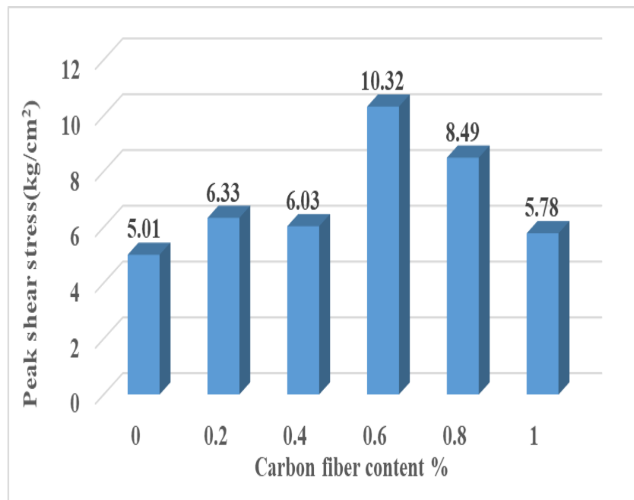
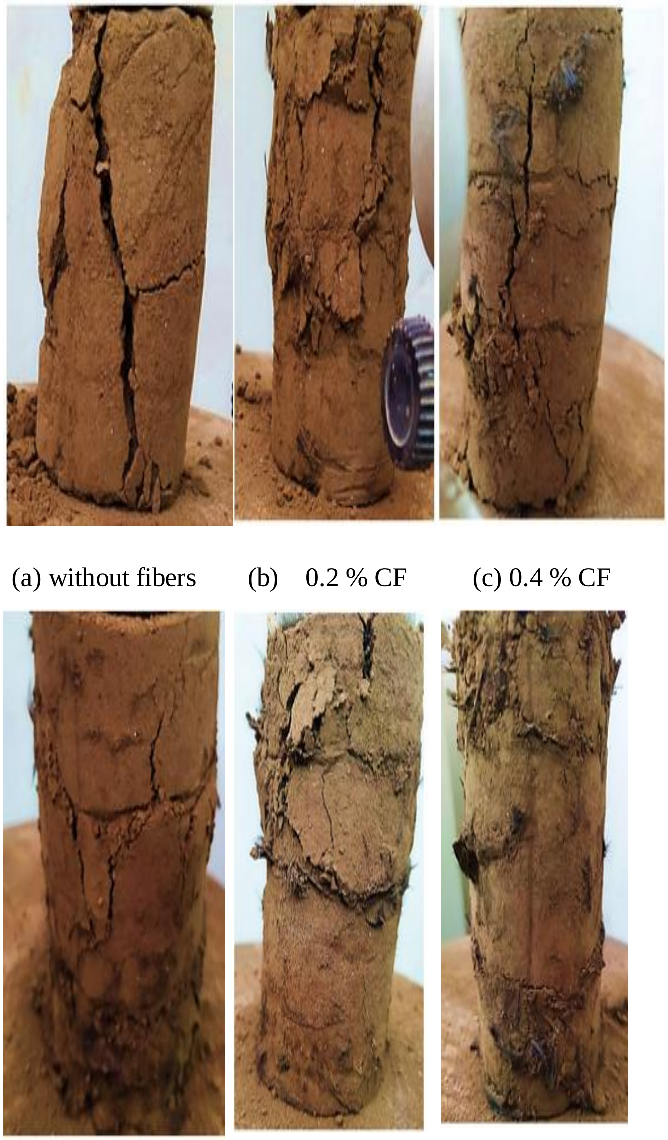


Fig. 6 Effect of carbon fibers on unconfined compressive strength.

In addition, the CF concentration determines the failure mode of samples during the unconfined compression test. Unreinforced samples failed along the vertical axis with a split-off failure. Failure of the shear bands was detected for soil samples with varying CF contents, and a V-shaped failure was reported for the 0.6% CF sample as shown in **Fig. 7**. The results indicate that adding CF may cause the reinforced samples to become more brittle. Other researchers have reached similar conclusions on the failure mode of samples **[14]–[17]**.



(a) without fibers (b) 0.2 % CF (c) 0.4 % CF

(d) 0.6 % CF (e) 0.8 % CF (f) 1 % CF

Fig. 7 Unconfined Compression Tested Specimen at Failure.

3.3. Compaction characteristics

The curves of CF-reinforced soils demonstrate a lowering in maximum dry density and an increase in optimum moisture content **Fig. 8**. The compaction curves of the reinforced soil are significantly lower than those of the non-reinforced soils. The maximum dry unit weight decreased from 1.62 g/cm^3 to 1.51 gm/cm^3 for CF-reinforced soil, which decreased by 7.28%, and the optimum water content increased by 4.6%. The optimum moisture content and maximum dry density for non-reinforced soil and soil reinforced with optimal CF content are shown in **Table 4**.

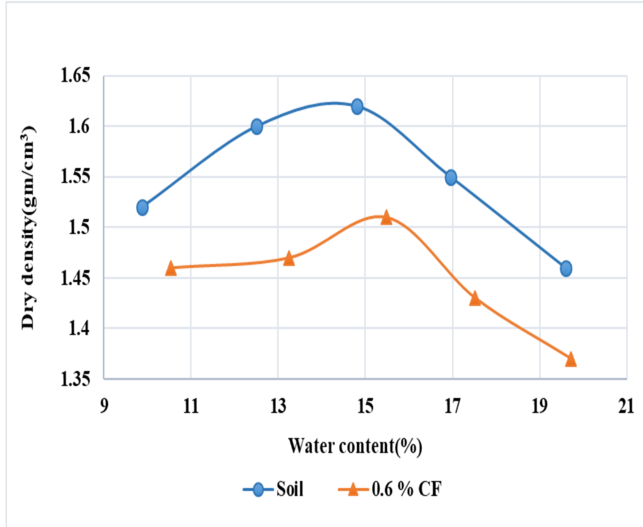


Fig .8 Compaction curves of CF reinforced soil.

Table 4 Optimum water content and maximum dry density values.

Soil sample	OMC %	γ_d max (gm/cm^3)
Natural soil	14.8	1.62
0.6 % CF	15.48	1.51

Sujatha et al. **[18] [19]** maximum dry density slightly decreases as lighter fibers replace heavier soil particles within a given volume. A lower maximum dry density is also caused by soil fibers resisting compaction, leading to bigger voids within the soil matrix. Several researchers that examined the effects of reinforcing soil with various fibers found similar results **[20]–[22]**.

3.4 Carbon fiber's effect on undrained shear strength

Fig. 9 demonstrates the relationship between normal stress and shear strength for a soil sample with varying CF contents as compared to a specimen without reinforcement. Soil samples reinforced with 0.6% CF have a higher shear strength than non-reinforced soils with the optimal water content as well as those with the natural water content. When exposed to normal stresses of 50 kPa, 100 kPa, and 200 kPa, the peak shear strength of soil reinforced with 0.6% CF was 70 kPa, 92 kPa, and 140 kPa, respectively. **Fig. 10** illustrates the influence of CF on the shear coefficients of soil, where the cohesion strength of soil reinforced with 0.6% CF was 46 kPa, which is higher than the cohesion strength of non -reinforced soil.

Due to fiber-soil contact friction, carbon fiber is effective at increasing internal friction angle and cohesiveness. Carbon fiber is supposed to provide friction between the soil and the complex network structure, so consider increasing the cohesiveness of the soil. Due to the rise in frictional angle and internal cohesiveness, soil shear strength can be increased. On the other hand, the short carbon fiber reinforcement, when dispersed uniformly in soil, not only adds to interlocking effects but can also fill a portion of the pores. In addition, the short carbon fiber might strengthen the stiffness of the soil. Carbon fibers may inhibit the spread of stress cracks and soil deformation, contributing to improved stiffness.

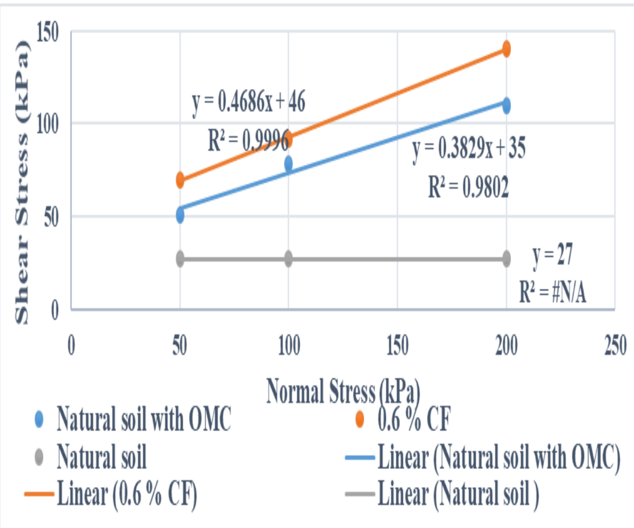


Fig. 9 The relation between normal stress and shear strength of samples soil.

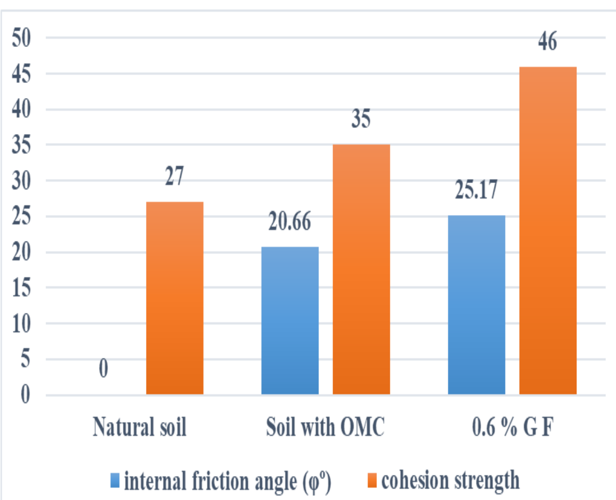


Fig. 10 Relation between the type of soil and shear coefficients of soil.

4 Conclusions and Recommendations

The effect of carbon fibers on the mechanical properties of soft clay soils through a series of unconfined compression tests, direct shear tests, and compaction tests were studied. The addition of fibers improved the geotechnical properties of the soft clay soil, most especially in unconfined compression strength values. The findings from this study are as follows:-

- Carbon fiber content affects the mechanical properties of soft clay soils.
- The liquid limit of soil reinforced with CF increased at the maximum fiber content of 1% by 7.41%, and the plasticity index decreased by 18.93%.
- At a fiber content of 0.6%, the unconfined compressive strength of soil samples reinforced with CF increased by 105.99%. The addition of carbon fibers also improved soil cohesion by 70.73 % and the angle of internal friction.
- When fiber was added, the optimal water content increased as the maximum dry density decreased. By adding CF, the sample of soil can be significantly strengthened. The rough surface of CF, when subjected to external loads, can contribute to the interlocking network structure and regulate the movement of soil particles.

However, more investigation is needed to fully comprehend the reinforcement mechanism of CF on clay soil, as well as to explore its mechanical performance. The other important characteristics of clay soil, such as permeability, time-dependent deformation, stability, and durability under various loading conditions, should also be taken into account.

List of Abbreviations

LL : Liquid limit

PL : Plastic limit

CF : Carbon Fiber

ASTM : American Society for Testing and Material

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