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Extension of Fly Ash Usability by Inclusion of Randomly Oriented Fibres

Tereza Čiháková
CTU in Prague, Department of Geotechnics
Thákurova 7, Praha 6, Czech Republic, 166 29
tereza.cihakova@fsv.cvut.cz

Abstract **–**Despite the great development of nuclear energy in the recent years, many countries are still dependent on energy produced by the thermal power plants today. In the thermal power plants, the energy is produced by combustion of coal. Fly ash is produced as the by-product of coal combustion. If there is no reuse of this material, it becomes the waste and it must to be stored in the landfills or tailing dams. These ways of storing represents huge environmental burden. The paper is focused on the possibility of reusing fly ash in the earth structures. The fly ash properties are very suitable for utilization in the earth structures. In the Czech Republic, only about one quarter of the total produced volume is re-used nowadays. Thus, we must try to achieve higher utilization. Therefore, the article is focused on the method of improving of the fly ash geotechnical properties- reinforcing by short randomly oriented fibres. At first, the principle of this method is presented in the paper. Thereafter, the laboratory test results (unconfined compression strength test and direct shear test) and the possibility of utilization of this material are presented.

Keywords**:** Fly ash, Fibre reinforcement, Geotechnics, Laboratory tests, Earth structures.

1. Introduction

Despite the great development of nuclear energy in recent years, many countries are still dependent on energy produced by the thermal power plants today. These power plants gain energy from combustion of coal. In the Czech Republic, the process of the thermal energy production has gone through the considerable modernization e.g. desulfurization, so that the negative environmental impacts have been minimized. However, a major disadvantage of thermal power plants is the fact that large amount of waste is produced during the combustion process. These secondary raw materials are generally called coal combustions products. This term includes e.g. fly ash, bottom ash, slag and flue gas desulfurization gypsum. If there is no further use of this material, it must to be stored in the landscape which is not in accordance with the principle of the sustainable development.

2. Production and Reusing of Fly Ash

Fly ash is a by-product from coal combustion process. Fly ash is contained in the gas. Prior to discharge to the atmosphere, the gas is blown into the separator in which the fly ash is absorbed. Electrostatic filters can capture almost 99 % of the amount of fly ash in the gas. However, fly ash can arise not only by combustion of coal but also by combustion of e.g. the municipal waste. Although all types of fly ash have very similar physical properties, chemical properties differ significantly. This paper deals only with fly ash from coal combustion in the thermal power plants.

In the Czech Republic, most of the energy (about 67%) is produced in the thermal power plants. Major of these plants burn lignite. For practical reasons, they are situated immediate to mines in the northern and north-western parts of the Czech Republic. About 50 million tons of brown coal is processed every year and simultaneously 14 tons of coal combustion products (CCPs) are produced (Web 1). These are very high numbers with the comparison with the rest of Europe. The annual production of CCPs in Europe (EU 25) is about 100 million tons (Feuerborn, 2011). In the term of per capita, Czech

Republic becomes the one of the biggest producer in the Europe. Annual production of fly ash is 10 million tons in the Czech Republic. Only 20 – 30 % of fly ash is further reuse in the construction engineering, the rest is stored in the landfills or tailing dams. In the construction industry, the most common way of reuse of fly ash is in the concrete production and as a replacement of soil in the earth structures.

This paper is focused on the second option. When used in the earth structures, fly ash replaces nowadays very valuable soil and it can be advantageously used in the sites where no suitable local soil is. Generally, fly ash has good properties for using in the earth structures. It can be used on soft soils due to its relatively low bulk density. Another advantage is the low prize of fly ash but it can rises with the transport distance. The disadvantage of fly ash can be seen in its varying properties depending on the thermal power plant.

The most common use in the earth structures is in the form of wet fly ash (agglomerate) and stabilized fly ash (stabilizer). Stabilization is the method of fly ash treatment. In this method, the pozzolanic properties of fly ash are used. Thus the fact that fly ash mixed with water and small amount of lime or cement tends to harden in time. This mixture is usually called stabilizer. Stabilizer is produced directly in the thermal power plant in the mixing centre. This material finds considerable utilization nowadays. In the Czech Republic, the standards and guidelines for the use in the earth structures have been developed.

This paper is focused on the less known method of fly ash improvement – reinforcing fly ash by small randomly oriented fibres. This method is relatively new. Research has been focused mainly of reinforcing of soils in the past. However, the laboratory tests carry out that fly ash can be very suitable for this method.

3. Fibre Reinforcement Method

Generally, the soil has good properties in compression while its tension strength is practically zero. This fact led to the idea of reinforcing the soil by the elements which can resist tensile stresses. The analogy can be certainly found in the reinforcement of the plain concrete. At present, we can divide soil reinforcement method into two main directions: macro-reinforcement and micro-reinforcement.

First method is widely used nowadays. It is used in the construction of earth structures in branch of transport structures, retaining walls, dams etc. In this method, the improvement of soil properties is achieved by embedding of reinforcement among the soil layers. Plastic strips, the geotextiles or the geogrids are usually used as the reinforcement.

This paper is focused on the second method: micro-reinforcement. In this method, small amount (usually 0,5 – 4% of soil weight) of short randomly oriented fibres is mixed with the soil. Fibres can be synthetic or natural origin. Natural fibres are e.g. coconut shells, sisal, hemp or jute. Geogrids or geotextiles that have been cut into small pieces were initially used an artificial fibres. With later development, short plastic fibres which are originally used in fibre concrete have been applied. These are polypropylene, polyester, polyamide or nylon fibres.

With some exaggeration, it can be said that the fibre reinforcement of soils has been used by people since the Middle Ages. For example, earthen buildings were reinforced by branches, reeds or straw. The Great Wall in China consists of clayey soil with tamarisk branches (Saran, 2011). The positive effect of root penetration on slope stability was also used in the past. However, in the modern conception, the fibre reinforced method is known for approximately 30 years. Previous research has been focused mainly on reinforcing sandy soils. It was proved (e.g. Gray et al. 1983, Michalowski 2002) that fibre reinforcement of soil causes increase of shear strength, reduction of the post peak strength loss, increase ductility and provides erosion control. The main advantage of fibre reinforcement method compared to macro-reinforcement is the fact that it is an isotropic composite material. There are no potential failure surfaces. In macro-reinforcement method, the potential failure surfaces are determined to be parallel with geosynthetic layer.

The main advantage of this method is the possibility of use of low-quality local soil, the ability to create steep slopes and thus minimize land take, insensitivity of structures to settlement etc.

Especially sandy and fine grained soils are suitable for fibre reinforcing method since their diameter of grains do not considerably predominate the length of fibres. Therefore, the gravel soils are not suitable because of its large diameter of grains. Clay is another example of unsuitable soil for this method because it tends to make clods after mixing with water and the homogenous mixture cannot be obtained. Fly ash appears to be very suitable material for fibre reinforcement method. The inclusion of fibre is very easy, fly ash does not make clods and furthermore it is advantageous from economical point of view.

4. Laboratory Testing

In order to use reinforced fly in the structures, it is necessary to carry out laboratory tests to find out the geotechnical properties of fly ash. In the first phase of laboratory testing, the plain fly ash properties were studied. Fly ash from the thermal power plant Mělník has been chosen which is certified for use in concrete structures. It is lignite fly ash, which represents the most common type of fly ash in the Czech Republic. Its chemical composition, grain size distribution, compaction properties and compressibility has been examined. Selected properties are summarized in the table 1.

Table 1. Selected properties of tested fly ash

Specific gravity	2040 kg.m^{-3}
Grain size distribution	
Sand Silt Clay	29.4 % 70.6 % 0 %
Optimum water content	22 %
Maximum dry density	1252 kg.m^{-3}

Next phase of the research has been focused on the fibre reinforced fly ash. Small plastic fibres, which are originally used in fibre concrete, have been chosen. These are polypropylene fibres Forta Ferro and can be seen in the picture 1. Length of the fibres was adjusted so that the length (13mm) suits to the sample dimensions.

Fig. 1. Fly ash (left) and propylene fibres Forta Ferro (right).

With respect to limited scope of the article, the paper is focused only on two laboratory tests: unconfined compression strength test and direct shear test. On these types of test, the influence of fibres can be easily demonstrated. Three types of tested mixture with different fibre content (0%, 1%, 2%, related to the dry unit weight) were prepared. Fly ash was first mixed with water to the optimum water content which was determined by Proctor standard test. After addition of water, fibres were mixed with fly ash. It was proved that the reverse process (mixing fibres with the dry fly ash) is unsuitable because fibres tended to make clumps.

4. 1. Unconfined Compression Strength Test

The unconfined compression strength (UCS) is a very important characteristic that is primarily used in the earth structures design. The unconfined compression test is a laboratory test in which a cylindrical sample is stressed by the axial force until failure. UCS is the stress at which failure occurs. Not only stress is recorded, but also the deformation of the sample and therefore the sample strain.

In these tests, cylindrical samples with the diameter of 38 mm and the height of 76 mm were prepared. All the samples were compacted using the hand tamping to the mould of given dimensions. This sample was placed in the press and tested. Three samples at the minimum were always tested for each mixture.

The graphical representation of the test results is in the figure 2. There are 3 curves – for the unreinforced fly ash, the reinforced fly ash by 1% and 2% content of fibres. The graph shows the dependence between the axial stress and the vertical strain.

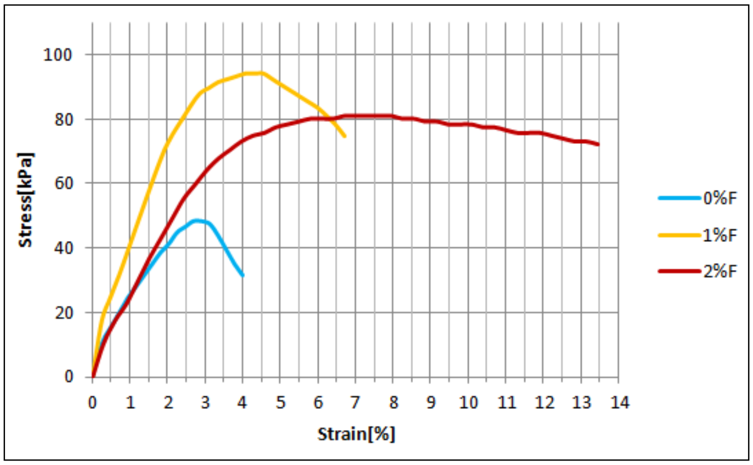

Fig. 2. Stress-strain behaviour of fly ash in UCS test.

Fig. 3. Disturbed samples after UCS test (0%, 1% and 2% of fibres).

The unreinforced sample reached the maximum axial stress 48.5 kPa at 2.9% strain. After that slip surface created very quickly and the sample collapsed. The slip surface is shown in the picture 3.The fly ash reinforced by 1 % of the fibres reached maximum stress 94.4 kPa at 4.6 % strain. Smaller slip surface developed in the part of this sample (fig. 3). The fly ash reinforced by 2 % of fibres reached the maximum value of the stress 86.4 kPa at 5.8 % strain. The sample was further deforming, but a significant slip surface was not created and the sample didn´t fail (fig. 3).

The unconfined compression tests proved that the reinforcement has an essential and positive impact on the stress-strain behaviour of the fly ash. The fibre reinforcement leads to increasing UCS (in some cases up to twice as much). However, this tension is achieved at the expense of the larger relative deformation (this was also proved by edometric tests). The main difference in the behaviour of the unreinforced and the reinforced fly ash occurs after reaching the maximum axial stress. While the unreinforced fly ash fails very early after reaching the peak stress, the reinforced specimens are very ductile. Laboratory testing also demonstrated that there is no significant development of the slip surface as in the fly ash without the fibres. This property was observed especially in fly ash with the 2 % of fibres.

4. 2. Direct Shear Test

Direct shear test is a laboratory test which is used to study shear behaviour of tested soil. From this type of test, we can obtain the shear parameters – friction angle (φ) and cohesion (c), which are very important while designing earth structures. We can also observe stress-strain behaviour of tested material (e.g. peak strength and residual strength).

Fig. 4. Testing apparatus (left) and reinforced sample after the test (right).

Tested sample has square cross- section with the size 84 x 84 mm. The height of the sample is usually 20 – 25 mm. The box has two parts, one is movable. The wet fly ash samples were prepared directly in the shear box by tamping of fly ash until the desired density was obtained. Four samples were prepared at the same time. Samples were closed in the shear box and then the vertical stress was applied. Each box was loaded by different normal stress: 50, 100, 150 and 200 kPa (Testing apparatus is in the figure 4). After consolidation, which usually took 12 hours, the shearing could begin. The sample is loaded until reaching displacement of 10 % of the box size (8.4 mm). The sample after the test is in the picture 4.

In the course of shearing, the shear force and displacement is recorded. After data processing, we can obtain curve of shear stress- displacement dependence curve. This curve for normal stress of 200 kPa is in the figure 5. There are three curves representing different fibre content. The shear parameters have been carried out for each mixture. For unreinforced specimen, the friction angle is 25.9° and cohesion 38.9 kPa. For specimen reinforced by 1% of fibres φ is 26.3° and c is 45 kPa. Finally 2% fibres increased friction angle to 27.8 °and 46 kPa.

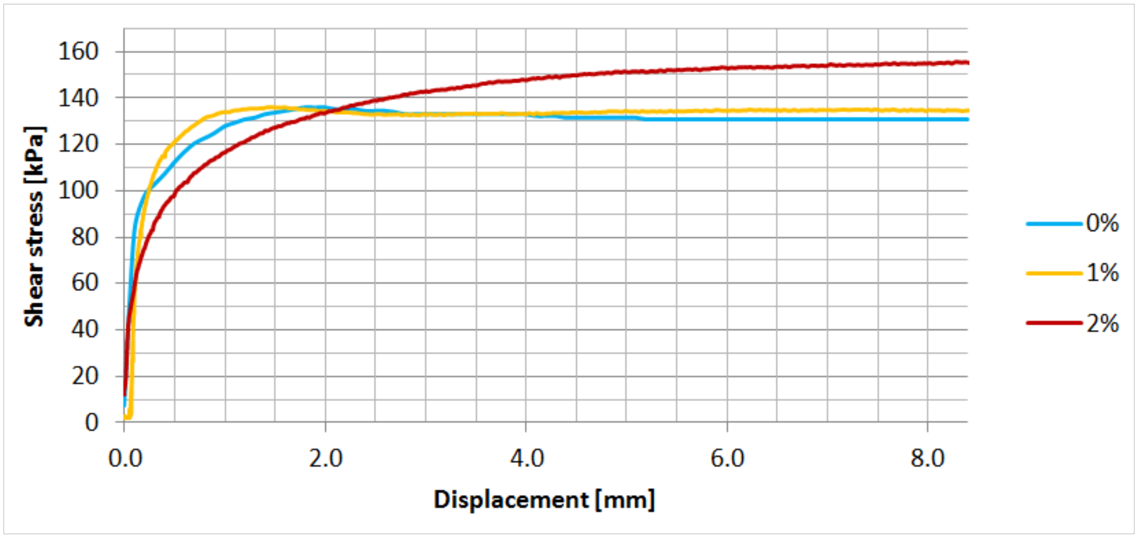

Fig. 5. Stress – displacement dependence for samples under normal stress of 200 kPa.

Direct shear test proved the fact that inclusion of fibres causes high ductility of the material and also reduces post peak strength loss. This can be mainly seen at 2 % fibres mixture. No peak strength value was observed in 2% mixture. Also change in the value of φ and c can be observed. Inclusion of fibres increases the cohesion and also the friction angle of fly ash. Therefore, we can say that inclusion of fibres probably increases the shear strength of fly ash. Several past researches (Kaniraj et al., 2003, Kumar et al., 2005) also proved that fact. However, the relatively high values of the cohesion of compacted samples probably exhibit apparent cohesion due to capillarity stresses. In present, triaxial consolidated drained tests are performed to confirm the results from direct shear test.

5. The Possible Applications

Fibre reinforced fly ash could be used in the following structures:

- Embankments – reinforced fly ash enables to create steeper slopes and thus minimize land take. Fly ash is a relatively lightweight in comparison of soils thus can be favourably used for embankments on soft soils.
- Retaining walls backfill - fly ash could exert lower pressure than soil.
- Improvement of subsoil - increase of bearing capacity of subsoil
- Rehabilitation of underground cavities – cavities caused by the demolition of previous structures, tunnel structures or sewerage
- Recultivation of landscape which was affected by mining in the past
- Subsoil of high loaded areas – e.g. airports

If the fibres are mixed into the stabilized fly ash, its utilization would be even wider especially in the construction of roads. For example:

- Construction of sub grade – so called active zone, the upper layer of road earth structure
- Pavement base layers –the traffic load is distributed there. In the case that normally used concrete would be replaced by fly ash, it could be a considerable difference in costs of structure.

6. Conclusion

Application of randomly distributed short plastic fibres brings opportunity to extend the utilization of the waste material in earth structures. This theme seems to be topical nowadays, thus at a time when annual production of fly ash increases every year and fly ash disposal has to be solved in accordance with sustainable development principles. Only about 20 – 30% of fly ash is re-used every year in the Czech Republic. From this is obvious that we must try to find new ways of re-using this material. In this paper, one of the methods of improvement of fly ash properties has been presented -the fibre reinforcement method. Several geotechnical laboratory tests were carried out to study the influence of fibre inclusion.

The paper is focused on two laboratory tests – unconfined compression strength test and direct shear test. Results of the experiment show that inclusion of fibres causes positive changes in the behaviour of fly ash. Particularly, it is the ductile behaviour of fly ash mixed with fibres and the reduction of post peak strength loss. Increase in shear strength will be verified by the series of triaxial consolidated drained tests. The possible applications of this material are also presented in the paper.

Results from laboratory tests provide valuable information about the geo-mechanical characteristics of the material which must be necessary known while designing the earth structure. However, to achieve wider use of reinforced fly ash in practice, it is also necessary to focus on problems associated with the technology of production and construction. The research will be also concentrated to design method of earth structures from this material. As well as in the field of fibre concrete, big challenge can be utilization of recycled fibres e.g. tyres fibres instead of plastic fibres. This will be also part of further research.

Acknowledgements

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