Utilization of Lightweight Tetrapod Aggregate Produced from a High Calcium Fly Ash in Civil Engineering Applications

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ABSTRACT

Due to the increasing volumes of fly ash production in some countries that depend on coal for running their thermal power plants, new utilization areas must be found. One of these areas is to utilize large volume applications such as the production of special shape aggregate (tetrapod) to be used in different geotechnical applications and highway construction. This is beneficial in solving the disposal problem of fly ash as well as making economical use of a mineral resource. To achieve these goals, fly ash was utilized in producing tetrapod shape lightweight aggregate by pressing into a specially designed mold. Pre to the production of tetrapods, regular lightweight fly ash aggregates were produced, cured and tested. Test results on the regular lightweight fly ash aggregates were implemented in the production of tetrapods. Optimization of lime content showed that five per cent by weight lime addition to fly ash had the best performance. Tests were conducted on the cured tetrapods in order to determine their mechanical and physical properties. Absorption and other properties were improved by surface treatment with water glass and heating.

Keywords: Fly Ash, Lightweight Aggregate, Tetrapod, Lime, Durability, Water Glass, Mechanical Properties.

INTRODUCTION

Industrial by-products have been receiving considerable attention because the public have become more aware of the effect of the surrounding environment on their health, thus they have become more environmentally conscious. This demands that special attention should be paid either to their proper disposal or utilization in order to minimize pollution. It is true to say that these by-products are being produced in huge amounts all over the world and that their disposal has become a major issue of concern.

Among all the industrial by-products produced worldwide, fly ash is generated in the largest quantity (Sarkar et al., 1995). Despite over six decades of fly ash use in the construction industry, it is still true to estimate the global disposal of fly ash as waste with more than 70 per cent of the generated fly ash (Mehta, 1989). Research has provided wide range of areas for utilization of fly ash, among these areas is the utilization in cement and concrete as a blending component (Frohnsdroff, 1986), in addition to raw material and fuel in the kiln cement clinker production (Bijen and Waltje, 1985). Another worldwide utilization of fly ash is in the industry of lightweight fly ash aggregate which finds many applications in the civil engineering projects. In this industry palletizing of fly ash forms the basic step. The formation of pellets from fly ash particles can be accomplished by using a cold-binding or sintering

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technique (Yamashita et al., 1995; Baykal et al., 1994). Binding materials, such as lime and gypsum, are used within this process. The final step in the production method is the curing of fly ash aggregate. The temperature, humidity and pressure applied during the curing process and the duration of curing are the most important parameters.

This study aims at utilizing fly ash as a waste material produced in the power plant into the production of lightweight fly ash tetrapod aggregate by cold binding and pressing into a specially designed mold. The tetrapod shape was selected among many other possible shapes because it is believed that the tetrapod shaped particles together provide strength and permeable structure. The strength is provided by the good interlocking provided by the legs of the tetrapod, while high permeability is guaranteed by the large spaces between the particles. In the production of the tetrapod aggregate, lime as a binder is used to improve the physical and mechanical properties. The absorption and soundness properties of the produced tetrapod aggregate were improved by heat and surface treatment using water glass.

Table 1. Chemical Composition and Physical Properties of Fly Ash.

Chemical Analysis		Fly Ash (%)
Silicon dioxide,	SiO_2	47.20
Aluminum oxide,	Al_2O_3	25.56
Iron oxide,	Fe_2O_3	5.64
Calcium oxide,	CaO	14.49
Magnesium oxide,	MgO	2.04
Sulphur trioxide,	SO_3	2.74
Physical Properties		
Blain fineness		382 m^2/kg
Relative density		2.22
Loss on ignition		1.10 %

METHODOLOGY

Materials Used

Approximately 1 ton of fly ash was used to finish this study. After sampling, the fly ash was sealed to prevent carbonation and any increase in its moisture content. The physical and chemical properties of the fly ash are given in Table (1). The Blain fineness is 382 m^2/kg, the mean diameter is 17.7 µm and the specific gravity of the fly ash is 2.22. This is a high calcium fly ash, with self-cementitious properties. The SO_3 content is less than 5 % and the loss on ignition is 1.1%.

Lightweight Fly Ash Aggregate Production Technique

The flow diagram shown in Figure (1) shows the aggregate production technique used in this study. The production technique is divided into two phases. Phase I was done on regular lightweight fly ash aggregate in order to optimize the lime content and the curing conditions. The results obtained from phase I were used for the production of the tetrapods in phase II. In phase I, regular lightweight fly ash aggregate are produced by mixing fly ash with 5%, 10% and 20% by weight of hydrated lime. These percentages were arbitrary selected. Going up more than 20% lime content will be neither economical nor practical, while less than 5% lime content has no effect. The water content used in mixing was to the wet side of the optimum water content obtained from Standard Proctor test (ASTM D698). Pellets are formed by continuous manual mixing. The pellets are sieved through different size sieves. The aggregates produced are placed into a curing room for 28 days. The curing conditions are 80% humidity and a temperature of 21ºC. After the completion of curing time, specific gravity, water absorption (ASTM C127), Los Angeles abrasion test (ASTM C131), sodium sulphate durability, crushing value (BS 812), California Bearing Ratio (AASHTO T193) and point load tests were conducted. Radiographic pictures of the cured and uncured aggregates were taken to observe any density change and cracks in the aggregates, and it was observed that the pelletization technique used was adequate. This judgment was justified by the radiographic picture taken which showed densification progress (due to hydration) without any crack formation. Finally, to improve the properties of the produced aggregates, surface treatment with water glass was applied. The aggregates were immersed in water

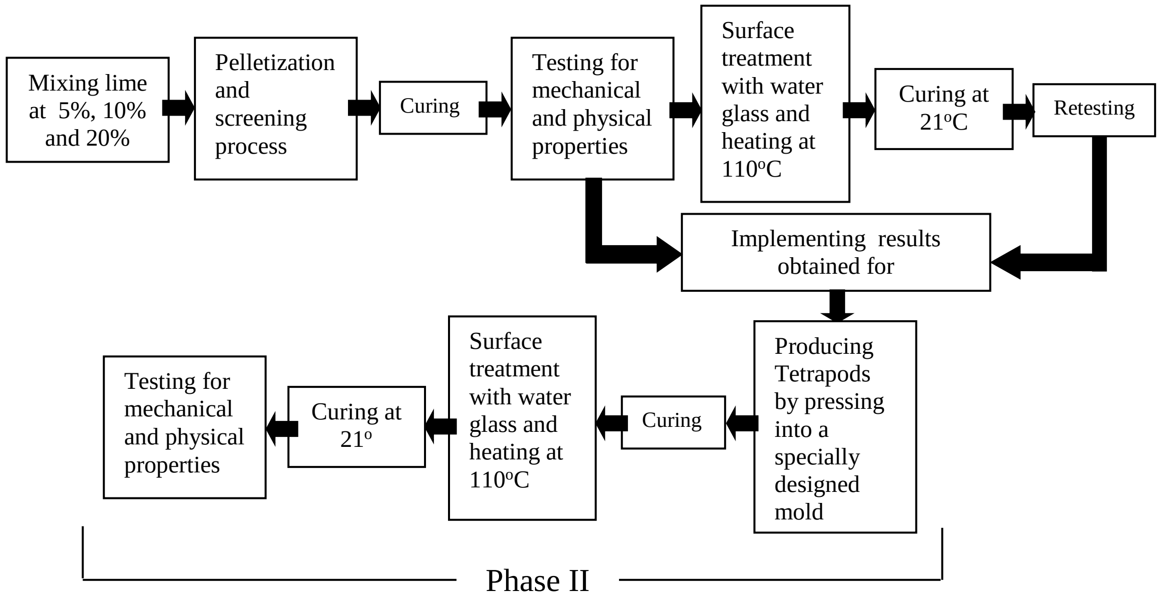


Figure 1. Outline of Tetrapod Aggregate Production Technique.

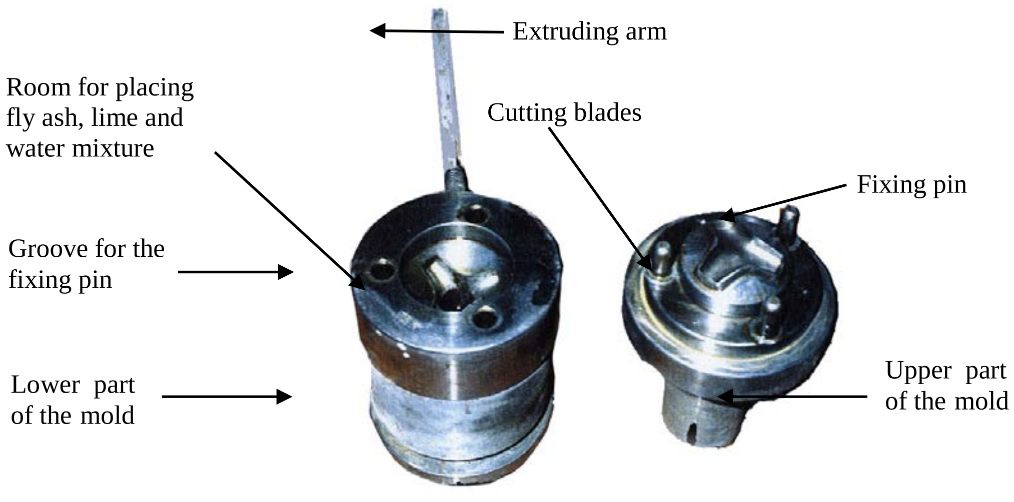
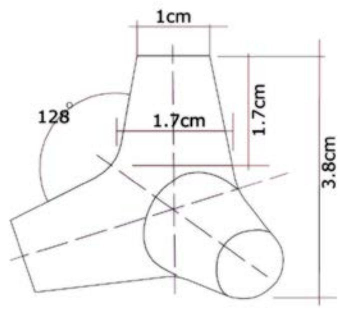


Figure 2. A Specially Designed Mold Used for Producing Tetrapods.



(a) **(b)**

Figure 3 (a). Tetrapod Aggregate. (b). Dimensions of a Tetrapod Particle.

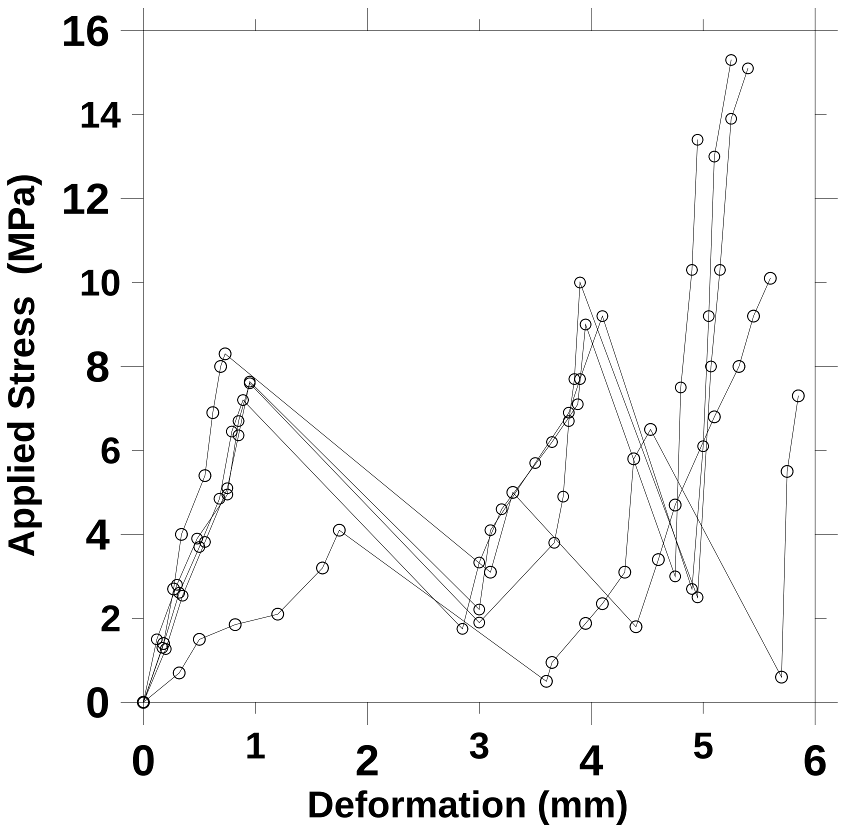


Figure 4. Behavior of Tetrapod Particles under a Direct Load Test.

glass for 10 minutes, and then they were dried by subjecting them to a jet of air. The dried surface treated aggregates were heat treated in an oven for 12 hours at 21ºC. The aggregates with surface treatment were sealed and cured at110ºC for 24 hours then tested for absorption, Los Angeles abrasion, crushing value and freeze - thaw durability.

Table 2. Test Results of Untreated Regular Fly Ash Aggregates.

Lime Content (%)	Specific Gravity	Water Absorption %	Los Angeles Abrasion Value (%)	Sodium Sulphate Soundness (%)	Crushing Value (%)	CBR Value (%)	Point Load Value (kg)
0	1.85	34.3	47.7	9.1	45.6	70	145
5	2.0	30.1	44.4	13.3	31.1	85	160
10	2.15	28.2	52.6	15.7	36.6	85	141
20	2.2	28.3	55.0	17.3	38.5	-	139

Table 3. Test Results of Untreated Tetrapods.

Lime Content (%)	Specific Gravity	Water Absorption (%)	Los Angeles Abrasion (%)	Sodium Sulphate Soundness (%)	Crushing Value (%)	CBR Value (%)	Point Load Value (kg)
5	2.3	27	38.6	11.4	27.4	87	-

Tetrapods Production Technique

In phase I, 5% lime content showed better performance. It resulted in a higher point load strength (160 kg), better Sodium Sulphate soundness than at higher lime contents (13%) and satisfactory CBR value (85%). These results are shown in Table (2). This percentage of lime (5%) was selected to be used in the production of the tetrapod particles in phase II. Tetrapod aggregate was produced by mixing fly ash with 5% lime and 25% by weight of water and then pressing into a specially designed mold (the mold is shown in Figure (2) under 800 kPa pressure. The CBR load frame was used in applying the pressing pressure. The load was applied on the upper part of the mold. The specimens were extruded by the aid of the blades that exist in the upper part of the mold and by the extruding arm attached to the mold. The specimens were then sealed and cured for 28 days at 21ºC. Figure (3) shows a sample of the produced tetrapod aggregate.

Table 4. Comparison Between Regular Fly Ash Aggregate and Tetrapod Aggregate (Both are prepared at 5% lime content, and surface treated with water glass).

	Regular Fly Ash Aggregate	Tetrapod Aggregate
Water Absorption (%)	14.3	12.7
Los Angeles Abrasion Value (%)	34.2	33.2
Crushing Value (%)	29.7	26.7
Sodium Sulphate Soundness (%)	10.1	9.3

Direct Load Test Conducted on Tetrapods

This test was performed in order to study the behavior of the tetrapod particles under direct axial stress, and to measure its compressive strength. In this test, the individual tetrapod particle was placed on its lower three legs, and the top of the upper fourth leg was subjected to a vertical load. In this test, the CBR loading frame was used. The load deformation relations were plotted for a total of 200 randomly selected tetrapod particles. Typical plots are shown in Figure (4).

RESULTS

The experimental results obtained for physical and mechanical properties of the produced regular fly ash aggregate in phase I are shown in Tables (2) and (4), while test results of tetrapod aggregate are presented in Tables (3) and (4), and in Figure (4).

DISCUSSION

Physical and Mechanical Properties

The test results presented above show that most of the physical properties were improved by increasing the lime content from 0% to 5%. For example, the specific gravity increased from 1.85 at 0% lime content up to 2 at 5% lime content, while the absorption value decreased from 34.3% at 0% lime content to 30.1% at 5% lime content. The results also show that aggregates produced with 5% lime addition had higher CBR; it increased from 70% at 0% lime content to 85% at 5% lime content. At the lower lime content of 5%, the freezing and thawing durability (indirectly measured by using sodium sulphate solution) is higher. It was found that after 10 cycles of freezing at -20ºC and thawing at 21ºC, the 9.1% weight loss after treatment at zero lime content; increased up to 13.4% at 5% lime content. Los Angeles abrasion value was decreased from 47.7% at 0% lime content to 44.4% at 5% lime content. The strength of the particles measured by the point load test was also improved. The failure load increased from 145kg at 0% lime content up to 160 kg at 5% lime content. At higher lime content, physical properties were adversely affected.

Based on the above results, 5% lime content was found to be the optimum, and this is why it was used in the second phase for tetrapod production. For the tetrapods prepared at 5% lime content, test results showed better performance for both physical and mechanical properties than the regular fly ash aggregate. This can be seen when comparing the results at 5% lime content for the regular fly ash aggregate in Table (2), and the results for the tetrapod aggregate in Table (3). It is believed that this is due to the pressing of the materials into the mold.

Surface Treatment and Heating

Other experiments were carried out where the regular fly ash aggregates as well as the tetrapod aggregate prepared with 5% lime content were treated with water glass and heated at 110ºC for 24 hours. Test results showed a dramatic decrease in the absorption value which was reduced from 30.1% before treatment to 14.3% after treatment for regular fly ash aggregate, while for tetrapod aggregate, it was reduced from 27% before treatment to only 12.7% after treatment. This is due to the fact that water glass and curing at relatively high temperature helped to seal pores on the surface, and to a certain extent, the internal pores. Heating at relatively high temperature allowed the water glass to penetrate into the inside of the particles, thus, filling the pores.

The abrasion value was also decreased after surface treatment and heating. It was reduced from 44.4% before treatment to 34.2% for regular fly ash aggregate, and from 38.6% before treatment to 33.2% after treatment for tetrapod aggregate. It is believed that the overall decrease in the abrasion value is due to the reduced friction between the particles due to the glassy surface of the particles after treating with water glass.

Crushing value also decreased after treatment. It decreased from 31.1% before treatment to 29.7% after treatment for regular fly ash aggregate, and from 27.4% before treatment to 26.7% after treatment for tetrapod aggregate. Again, the decrease in the crushing value is due to the loss in friction between the particles and not due to strength gaining. Strength gaining - if any- due to surface treatment is not significant; this is due to the fact that the water glass material is weak even after hardening.

Sodium Sulphate soundness was also improved after treatment. It was decreased from 13.3% before treatment to 10.1% after treatment for regular fly ash aggregate, and from 11.4% before treatment to 9.3% after treatment for the tetrapod aggregate. This reduction is due to the film of water glass that coated the aggregate particles, which in turn protected the aggregate particles from direct attack of the solution.

Behavior of the Tetrapod Particles Under Applied Stress in the Direct Load Test

The stress-deformation relationship for the tested tetrapod particles showed a multi peak behavior. Out of more than 200 tested specimens, 92% had three peaks for the stress - deformation diagrams while the rest had only two peaks. A sample of this behavior is shown in Figure (4). It is believed that the individual particle is subjected to different types of stress during the load application. Observations showed that at the beginning of load application, the edges of the three legs in contact with the lower testing frame base broke. As the specimen was further loaded, cracks at the upper ends of the lower legs started to appear and then the legs failed. In this stage of failure, the failure is due to tensile stresses that were induced at the upper ends of the legs. The stress-deformation diagram reaches its first peak when the first leg breaks; at the instance of breaking, the strength drops and the specimen rotates. The strength starts increasing again when the second and third legs start to carry the applied stress. When these legs broke down, the strength drops again forming the second peak. In this case, the failure is due to both tensile stress and bending moment. The bending moment is due to the eccentricity of the applied load due to rotation of the specimen after breaking of the first leg.

The final stage of the failure mechanism is related to the upper leg. Having the three legs failed, the fourth leg continues to resist the applied stress in pure compression. This is similar to the behavior of a cylindrical specimen subjected to compressive stress. In this stage, the compressive strength of the fourth leg is mobilized and the stress at failure represents the compressive strength of the material.

Fields of Application

More than one thousand tetrapod particles were prepared to measure the angle of repose (the minimum internal friction angle). A value of 62^{o} angle of repose was measured for the tetrapods, which is an indication of the good interlocking feature among the particles. The whole structure formed by the tetrapods is light in weight, permeable and of a satisfactory strength. These characteristics are perfect for many geotechnical and highway applications such as backfilling where the lateral load should be minimized satisfactory permeability. Tetrapods are perfect backfill material in the sense that they are light in weight and allow water drainage (which is essential in reducing water pressure) through the large voids between their particles.

Additionally combining tetrapods with open grid geotextiles can enhance the performance. It is believed that this combination is perfect for many geotechnical applications where strength, light weight and permeability is required. The strength of this combination comes from the good mechanical interlocking of the tetrapods legs through the geotextile grid openings.

Moreover, the behavior of the tetrapods under direct load (the multi peak behavior), where failure occurs in stages and not suddenly, makes it attractive in applications where dynamic and vibration loads are expected.

Another good application is in the construction of highway side slopes where steep slopes using tetrapods can be constructed due to their high internal friction angle. Tetrapods may also be used-if necessary-in road subbases. The CBR value (85%), and other specifications comply with the requirements for this application.

Furthermore, the special shape of the tetrapods and the shiny surface when treated with water glass make it attractive for many architectural applications due to aesthetic features.

CONCLUSIONS AND RECOMMENDATIONS

Producing lightweight tetrapod aggregates from high calcium fly ash is possible. The production process is believed to be simple, economical and with low energy consumption. This encourages the production at the industrial level. The produced tetrapods have many attractive properties from the civil engineering point of view. They are light in weight, sufficiently strong, highly permeable (in bulk) and have good interlocking. The tetrapod particles also have properties that comply with many common specifications. These features make it attractive to use tetrapod fly ash aggregates in a variety of civil engineering applications such as: backfill, embankment fill, highway subbase and highway side slopes.

Surface treatment using water glass and heating produced a glassy film on the surface of the tetrapods. This has truly improved the absorption and apparently improved the abrasion and crushing values.

It is highly recommended that a feasibility study is carried out to investigate the possibility to use tetrapod particles in commercial production.

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