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Strength Evaluation of Aggregate Made from Fly Ash

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ABSTRACT This paper is aimed to propose a strength estimation method for fly ash aggregate. The pellet strength is useful for predicting compressive strength of the concrete using the fly ash aggregate. By adopting the equation for a spherical solid under point load, the tensile strength of fly ash aggregate was derived from the simple point load test. Then the equation for estimating 30-day tensile strength of the fly ash aggregate produced from fly ashes with different chemical composition was proposed as a function of equivalent CaO content of the raw materials *ie* fly ash and cement. Since the strength of the fly ash aggregate increases with age, the maturity concept was introduced to compute the time-dependent tensile strength of the fly ash aggregate pellet based on the 30-day tensile strength equation. It was found that the tensile strength of the fly ash aggregate was higher when the equivalent CaO content of the raw materials used to produce the fly ash aggregate increased and the time-dependent tensile strength of the fly ash aggregate from ages 14 to 91 days could be fairly estimated from the maturity of the aggregate based on the 30-day tensile strength. This study will be useful as a tool for manufacturing and quality control of the fly ash aggregate.

KEYWORDS: fly ash, aggregate, fly ash aggregate, strength, strength development.

INTRODUCTION

Fly ash is the by-product from the coal generating plant. The annual production of fly ash in Thailand has reached nearly 3 million tons. Though there have been many studies and effort leading to practical use of fly ash in Thailand's construction industry, the utilization when compared to the production is still small (the consumption of fly ash increased from almost none in 1992 to about 300,000 tons in 1998). Therefore, it is necessary to introduce various methods of using fly ash other than the conventional use as cement replacing material. One of the supplementary effective methods is considered to be the use of fly ash to produce concrete aggregate. The research team of the first author had successfully produced concrete coarse aggregate from the Thai lignite fly ash (here-in-after called FAA) by non-sintering method.[1] Although getting lower quality product, the non-sintering process was selected in their study due to much lower energy consumption and lower cost in the production than the sintering method. The formation of FAA pellet was done by using a pelletizing pan. The research team also studied a two-phase material model for predicting strength and Young's modulus of concrete from the properties of mortar and FAA.[2] Also studied was the shear and bond behavior of the concrete using FAA.[3]

Since the strength of concrete made with FAA also changes according to the strength of the FAA, it is necessary to be able to estimate the strength of the FAA. The prediction of strength of FAA is also useful for preparing proportion of raw materials since the proportion affects the strength of the produced FAA.

For conventional aggregate, the crushing method by British Standard, where a bulk of aggregate particles are crushed by compressive load in a cylindrical container, is one of the popular methods for strength evaluation.[4] However, it is difficult to relate the crushing value obtained from the test to the compressive strength of the FAA made from the pelletizing method. Harada N, *et al*[5] proposed the method called "Monolayer loading test" for FAA, where a specified number of FAA pellets were arranged in one layer and then crushed with the compressive load in the direction normal to the plane of the layer. However, there are some difficulty in the application since the method required pellets with a single size to be arranged in the layer. Both methods also do not result in a simultaneous failure of all pellets. Therefore, the authors selected the point load test on individual FAA pellet for the strength evaluation. Though the method requires a number of repetition for a FAA to get a reliable test result, it is simple and compressive strength of the FAA can be computed from the breaking point load. Time-dependent strength of the FAA is also another issue covered in this study for more efficient quality control and production of the FAA.

Materials, Mix Proportion and Production of FAA

Materials and Mix proportion

Three types of lignite fly ash, FA(1), FA(2) and FA(3), obtained from Mae-Moh Electricity Generating Plant in Lampang province were used to produce FAA. The three types of fly ash have very similar chemical composition and physical properties as shown in Table 1. The reason for using three similar types instead of one type of fly ash is because of the insufficiency in quantity of each type of fly ash available in the laboratory. Ordinary Portland cement type 1 was used as the lime source for enhancing the binding property and strength of the FAA. The percentage of the cement in the fly ash-cement raw material was varied to change the strength of the FAA. The properties of ordinary Portland cement type 1 (OPC type 1) are also given in Table 1.

Table 2 shows the physical properties of the FAA samples produced in this study. Three types of FAA, denoted by FAA(1), FAA(2) and FAA(3), were produced for the study with the mix proportion shown in Table 2.

Production of FAA

To produce the FAA, the raw materials (fly ash and cement) were blended and poured into the pelletizer pan, having 1-m diameter, rotating on an inclined plane of about 45 degree. The pan was rotated with the speeds between 35 to 40 rpm. Water with the amount enough for agglomerating the FAA pellets was then slowly showered onto the powders. The pelletizer pan was continued to rotate until the firm spherical pellets are formed. The pellets were then put in fly ash powder for one day to prevent the pellets from being adhered to each other. Then pellets were then cured in water until the test ages.

Strength Prediction of FAA

Point Load Test for Obtaining Tensile Strength of FAA

For strength evaluation, the authors adopted the point load test, then compute tensile strength or tensile stress at the center of the tensile failure plane at the pellet breaking. Since the strength of FAA increases with time, it is necessary in the FAA production that the time-dependent strength of the FAA with varied raw material proportion must be

Table 1. Chemical composition and physical properties of powder materials in this study.

Material	Chemical Composition – Weight Percentage of Oxide (%)									Physical Properties	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	MnO	Specific Gravity	Blaine Fineness (cm^2/g)
FA(1)	43.24	23.18	8.81	10.26	2.92	2.57	0.2	1.24	0.087	1.93	2,643
FA(2)	41.58	22.5	8.88	10.4	2.84	2.48	0.18	1.26	0.089	1.90	2,444
FA(3)	42.86	23.05	8.75	10.13	2.93	2.55	0.2	1.17	0.087	1.94	2,739
OPC	21.45	5.35	3.01	67.33	1.52	0.33	0.11	2.31	-	3.15	3,741

Table 2. Physical properties of fly ash aggregates.

FAA Types	Proportion	Fineness Modulus (F.M.)	Specific Gravity	Absorption (%)	$(CaO)_{eq}$ (%)
FAA(1)	100% FA(1) + 0% OPC	7.30	1.31	21.72	10.26
FAA(2)	90% FA(2) + 10% OPC	7.37	1.37	21.63	16.09
FAA(3)	80% FA(3) + 20% OPC	7.03	1.42	19.45	21.57

predictable. The discussion in this paper is then emphasized on the evaluation of tensile strength, including the time-dependent strength, of FAA made with various fly ash-cement composition.

It is convenient to use the point load test for evaluating the load carrying capacity of the FAA pellet since the particle shape of FAA is usually nearly sphere [1]. Fig 1 shows the condition of point load test. The point load P is increased until the FAA pellet breaks. The maximum load P at the time of breaking is then recorded. The maximum tensile stress at the plane of failure is then computed and identified as the tensile strength of the pellet. For computing the tensile stress (tensile strength, σ_t) at the tensile failure plane at the time the FAA pellet breaks, the authors adopted the equation by Lur'e [6] for a spherical solid as shown in Fig 1 and in the following equation.

$$\sigma_t = \frac{P}{4\pi R_0^2} \times \frac{21}{7+5\upsilon} \qquad (1)$$

Where σ_t is the tensile stress at the center of tensile failure plane at the time of pellet breaking (MPa), P is the point load at the time of pellet breaking (N), υ is Poisson's ratio of the FAA and R_0 is the mean radius computed from three measurements in three normal direction of the FAA pellet (mm).

The value of Poisson's ratio of the FAA was reasonably assumed to be 0.25, then Eq (1) can be simplified to be

$$\sigma_t = 0.2\frac{P}{R_0^2} \qquad (2)$$

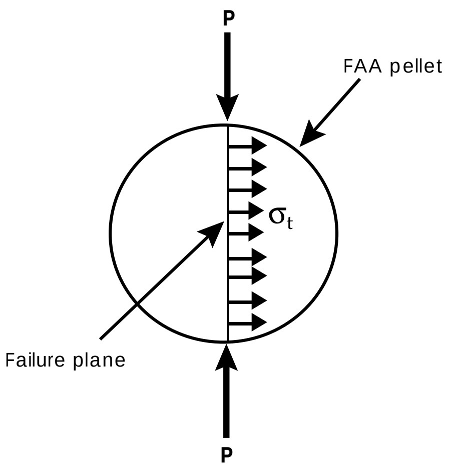

Fig 1. Point load test and tensile stress σ_t at the center of tensile failure plane.

Though compressive strength is more general in practice, it is difficult and not appropriate to test compressive strength of the FAA. For a compressive strength test, one must prepare either prism or cylinder specimen for the test. To use the standard cylindrical or cubic specimen as in the case of concrete is not proper because the way of casting the standard specimen is different from the way of forming the pellet by pelletizing. Also, though it is possible to prepare the cylinder or cube from the sphere-like pellet, it is very difficult and not practical. Too small specimen for compressive test also leads to a large scatter of the test result. It is popularly accepted in practice that the splitting tensile strength of concrete is related to its compressive strength. Therefore, it is reasonable to assume that there is a unique relationship between tensile strength and compressive strength of FAA which is a more homogeneous material than concrete. So, the compressive strength of FAA can be derived from tensile strength [2].

Tensile Strength Prediction of FAA with Different Fly Ash-Cement Proportion

In this study, the tensile strength of FAA was varied by changing the cement replacement, i.e. 0%, 10% and 20%. It has been proposed that in addition to the water to binder ratio, the CaO content in the total binders of the concrete is one of the important parameters for strength prediction of fly ash concrete [7]. It is then reasonable to assume in this study that the strength of the FAA varied mainly with the equivalent CaO content of the combined fly ash-cement raw material. The water to binder ratio in the production of FAA does not vary much since the water added during the pelletizing is for the agglomeration of the FAA. Water for strength development can be sufficiently supplied during the curing process. The equivalent CaO content, $(CaO)_{eq}$, can be computed from the following equation.

$$(CaO)_{eq} = \{r\,(CaO)_c + (1-r)\,(CaO)_f\}/100 \qquad (3)$$

where r is the weight percentage of the ordinary Portland cement (OPC) in the combined fly ash-cement raw material (%) for FAA production, $(CaO)_c$ and $(CaO)_f$ are the CaO content in cement and fly ash from the chemical analysis of the materials (% by weight of each material). The values of $(CaO)_c$ and $(CaO)_f$ for the cement and fly ashes in this study are given in Table 1. The values of $(CaO)_{eq}$ of FAA(1),

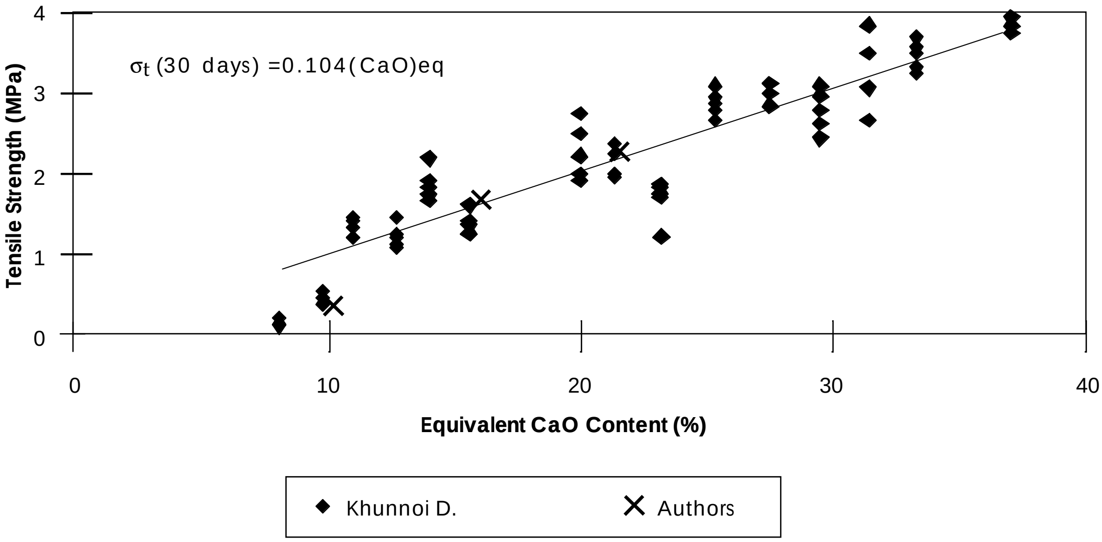

Fig 2. Relationship between tensile strength at 30 days and equivalent CaO content.

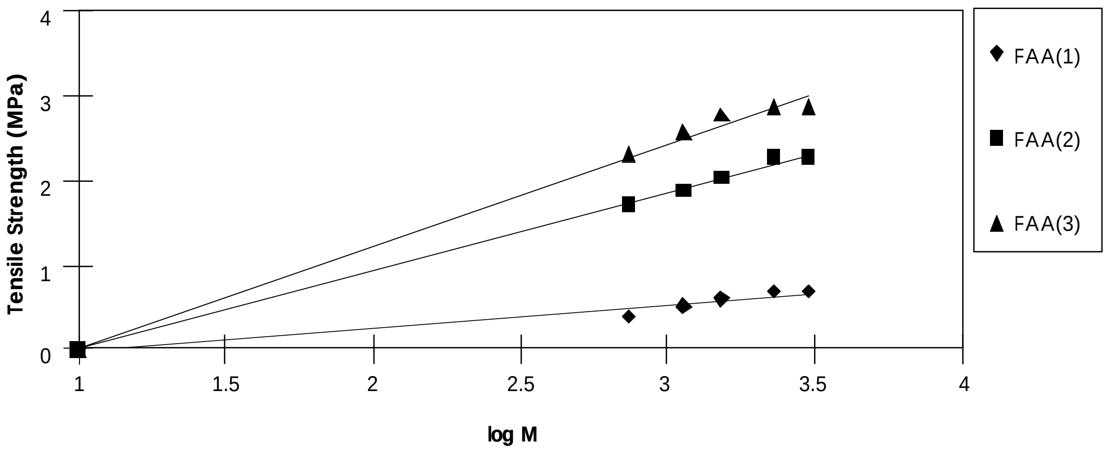

Fig 3. Relationship between log of maturity (log M) and tensile strength.

FAA(2) and FAA(3) were computed using Eq (3) to be 10.26%, 16.09% and 21.57% as given in Table 2, respectively.

From many point load test results of many FAA's, the relationship between 30-day tensile strength derived from the test and $(CaO)_{eq}$ of various FAA pellets can be summarized in Fig.2 and Eq.(4) as

$$\sigma_t(30 \text{ days}) = 0.104\ (CaO)_{eq} \qquad (4)$$

Although Eq (4) tends to overestimate much the tensile strength of the FAA with equivalent CaO content lower than 10%, the equation is considered useful for proportioning fly ash and cement for producing FAA with a specified 30-day tensile strength. It is worth noted here that FAA with equivalent CaO content less than 10% is not practical since the strength is too low for real application.

Time-Dependent Strength of FAA

It is known that strength of conventional aggregates does not vary with time, however, the strength of FAA is time-dependent due to pozzolanic reaction. To deal with the time-dependent strength development of the FAA, the maturity of the FAA was computed and related to the tensile strength. The FAA was cured in a standard water curing condition with the curing water temperature about 25°C. The maturity of the FAA, denoted by M, is defined as

$$M = \int_0^t T(t)dt \qquad (5)$$

where T(t) is temperature in °C which varies with time t, and dt is the time interval in days.

Maturity concept states that there is a linear relationship between strength and log M. However, it is believed that this linear relationship may not be realized in long term when the strength has been almost fully developed. Based on the tested 30-day tensile strength of the FAA, the tensile strength of the FAA at 14 days, 45 days, 60 days and 91 days were computed. The results of the test and the linear lines from the maturity concept using the 30-day tensile strength as the basis are shown in Fig 3. It can be observed that the maturity concept can be used to forecast the time-dependent tensile strength from ages 14 days to 91 days of the tested FAA with satisfactory results.

Conclusions

Based upon the results of this study, the FAA made from various fly ash-cement proportion were produced to study the tensile strength using the point load test. The equation for computing tensile stress at the tensile failure plane at the breaking point load was adopted. This tensile stress was utilized to represent the tensile strength of the FAA. It was found that the equivalent CaO content was one of the major parameters of tensile strength of the FAA. An experimentally derived empirical equation for computing 30-day tensile strength of the FAA was then obtained based on the equivalent CaO content. From this empirical equation, the maturity concept was introduced to predict the tensile strength at ages 14, 45, 60 and 91 days of the FAA. It was found that the obtained empirical equation and the maturity concept were applicable to a certain degree of satisfaction for predicting the tensile strength of the FAA made with the tested fly ash-cement proportion.

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