Flashag – New Lightweight Aggregate for High Strength and Durable Concrete

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ABSTRACT

A new patented lightweight aggregates is tested. This type is given the name Flashag. The only solid raw material used to manufacture these aggregates is fly ash. The aggregates are sintered but not pelletized and the process is easy and inexpensive. This paper describes these patented aggregates and compares them with other lightweight and normal-weight aggregates that are used for concrete. The paper presents the results of testing the aggregates for properties important in the concrete industry. The paper further presents the results of testing structural high-strength grade concrete made from the new aggregates. The results show that the concrete made from the new aggregates is lightweight, possesses low porosity, high strength and high durability potential. The results of the new aggregates are far more superior to previously known lightweight aggregates. High strength characteristics using Flashag are easily achievable with only moderate cement content. Even more significant, this new aggregate gave results that are superior to those of normal weight concrete that had the same cement content and comparable workability. The lightweight concrete made using this type of aggregates is more than 21% lighter than normal weight Granite and Dacite aggregate concretes. At the same time, Flashag concrete is about 15% to 21% stronger than high-strength normal weight aggregate concretes. Moreover, Flashag concrete possesses at least 30 % lower drying shrinkage value than normal weight high strength concrete and thus is much better in resisting shrinkage crack formation.

INTRODUCTION

The use of lightweight aggregate in concrete has many advantages. [1,2,3] These include: a) reduction of dead load that may result in reduced footings sizes and significant reduction in reinforcement, b) lighter and smaller precast elements needing smaller and less expensive handling and transporting equipment, c) reduction in the sizes of columns and slab and beam dimensions that result in larger space availability, d) high thermal insulation, and e) enhanced fire resistance. Furthermore, certain structures specifically offshore structures which are mostly used for oil production require lightweight elements which can be towed easily and have the greatest buoyancy. [4]

But perhaps the most significant potential advantage of the use of lightweight aggregates for concrete and building in general is the environmental value. When the raw materials needed for lightweight production are derived from industrial by-products, the environment and economy of the producing locality and country are deemed to benefit. Already, stringent environmental limitations are imposed on mining of natural aggregates in various parts of the world. [2,5] One of the more important of such by-products, if not the most important, is fly ash. Fly ash is a by-product of the burning of coal for power generation. Its collection and disposal is a necessary process in power stations. It was estimated that the world production of fly ash in the year 2000 was about 600 million tonnes. Of this amount, only about 9% get to be utilised. [6] In Australia, about 9 million tonnes of fly ash is produced annually. [6] Less than 10% of this quantity is used. [7]

Fly ash, however, is a material that has many proven advantages even when used in its raw form. [8,9] Such advantages, though very important and relevant, are not the subject of this article. This paper is about one particular advantage; namely the use in structural concrete of lightweight aggregate that is produced from fly ash. Such use would result in benefits to the community and the building industry. Among these benefits are the following: 1) Efficient recyclable disposal of the fly ash. 2) Helping to conserve the natural and very scarce materials of coarse aggregates and sand. 3) Sparing the countryside, river beds and beaches from the scarring and damaging activities of aggregate mining. 4) Producing aggregates much lighter than the natural aggregates which would result in the production of significantly lighter concrete whose advantages have been discussed above. 5) Improving durability and decreasing shrinkage cracking by drawing on the enhanced strength and bond of the concrete matrix to the aggregate. 6) Establishing an industry for lightweight aggregates with export potential especially to countries where natural aggregates are depleted or, are of extremely inferior quality as in the oil rich Middle East states. [10]

Reinforced concrete structures in coastal areas and off-shore structures are required to resist chlorides and sulphates laden seawater which bring about the grave dangers of chloride initiated corrosion of the reinforcement and sulphate ion attack on the concrete. Also, because many of the offshore structures are situated in cold regions, frost attack is another serious deteriorating factor that must be resisted. In addition, the possibility of exposure to hydrocarbon fire is present because of the structures' functions.[4] Many researchers have concluded that the use of lightweight aggregates derived from fly ash results in significant improvement in the resistance of concrete to deleterious effects as those mentioned above.[11,12,13] So far, offshore concrete structures have been constructed from aggregates derived from expanded shale, expanded clay, foamed slag and sintered fly ash. The performance of these structures has been closely monitored. [6,14] The published reports have been very positively in favour of this type of construction, being the most economical and efficient alternative.[7,11,14]

Sintered pelletized fly ash aggregates have been commercially produced in several industrialised countries such as the UK, USA, Japan, India, and North Europe. The manufacturing process of these aggregates requires pelletizing a mixture of the fly ash and water before sintering the pellets at 1300^{o}C. This process produces light spherical aggregate with high proportion of voids. The manufacture of sintered pelletized aggregate from fly ash requires a high degree of control during the production processes. The experience of the present author has shown large variations in the size and quality of the aggregate. Such variations have resulted, as expected, in inconsistency in the final product, namely, the concrete. [15] Since it is structural concrete that is ultimately the subject of interest, it is imperative that the produced aggregate should be of high quality and consistent characteristics. This is specially the case when such aggregates are to be used in important structures such as off-shore platforms.

The present author, together with co-inventor K. Shaw, has produced lightweight aggregates from fly ash. The product is now patented in the USA and several other countries. [16] The product is unique, easy to produce and possesses desirable and consistent qualities. This product, which the inventors have named Flashag, requires less energy, less workmanship and equipment than the pelletized sintered fly ash aggregates which are commercially available. The objectives of the inventors were the following:

1) To produce highly consistent aggregate from fly ash.
2) To use such aggregate in the production of structural concrete.
3) To develop a simple and easily controllable method that can be applied in large-scale production.
4) To demonstrate the superiority of the aggregates produced by this new technique over those produced by pelletizing, which is the only method that is most successfully applied so far.

In Australia, there is no production of lightweight fly ash aggregate by any method. This is in spite of the fact that most of the power industry in this country is from coal sources, and that fly ash itself is produced abundantly. Kayali and Haque [17] have investigated the use of sintered pelletized fly ash in high-strength concrete production and concluded that it is capable of producing concrete with compressive strength of 70 MPa. For this purpose, they used commercially available lightweight aggregate that has been manufactured since the 1960's. [14] Nevertheless, and as mentioned above, consistency and repeatability of the strength values and workability levels, even under the strictest laboratory conditions were not high. [15] The reason for this drawback is the inconsistency in the lightweight aggregate that was used. The inconsistency was manifested mainly in the water absorption capacity, hardness, and size distribution. Moreover, producing high strength lightweight concrete required a very large quantity of ordinary portland cement. For example, those authors [17] have produced high strength concrete in excess of 70 MPa using sintered and pelletized fly ash aggregates but had to include more than 500 kg of portland cement. However, the use of large quantities of portland cement should be discouraged as much as possible. This is because cement manufacture is an industry that causes significant damage to the environment through its very high demand of energy and its emission of very large amounts of carbon dioxide [6]. Thus, it has been found that in order to produce high performance concrete from the currently available pelletized and sintered fly ash aggregates, a substantial amount of cement must be used. This is quite defeating to some important purposes for which the lightweight aggregate concrete was envisaged in the first place.

In this paper, the author demonstrates that with the newly invented aggregate that has been manufactured from fly ash using a simple and repeatable method, it became easy to obtain superior and consistent results. The author has successfully used this aggregate for the production of structural high strength concrete. The author strongly believes that with this new lightweight aggregate the inventors have accomplished a breakthrough in the manufacture of lightweight aggregate from fly ash. This is because, not only the resulting concrete is far superior to other fly ash lightweight aggregate concrete made from the pelletized variety, but also it is even superior to traditional concrete made from Granite or Dacite aggregates. This superiority has been achieved without having to increase the cement content. This has resulted in producing a much lighter material that, at the same time, is stronger than traditional normal concrete. The product is workable, has low cement content, requires less stringent curing conditions and is of high strength and performance.

ASH AND AGGREGATES DETAILS

Ash sources:

Two series of experiments were made applying the methods of the patented invention. The first series used Class F fly ash conforming to ASTM standard.[18] This was obtained after the ash was screened and classified. The ash used in the second series was collected directly from the hoppers without any further screening. Table 1 shows the properties of the two ash types used in the two series.

The aggregates were manufactured through the patented process, which does not include pelletizing. The resulting aggregates are therefore of angular and rough surfaces. These aggregates are crushed to the suitable sizes using the crushing methods similar to those that produce normal weight aggregates.

Table 1-Properties of the Fly Ash used in the two series

Chemical constituent	Series 1 Percent by mass	Series 2 Percent by mass
SiO_2	58.2	55.4
Al_2O_3	28.5	25.5
Fe_2O_3	4.0	7.8
K_2O	1.50	1.1
TiO_2	0.9	1.7
CaO	1.6	4.1
MgO	0.8	1.0
Na_2O	0.4	0.3
P_2O_5	0.1	0.45
Mn_3O_4	0.1	0.07
LOI	1.9	1.25
Fineness (passing 45µm)	94%	65%
Specific gravity	2.28	2

Characterisation of the Aggregates:
Since the purpose of producing the aggregates is to use them in the making of concrete, the characteristics relevant to concrete making are those that the present author has determined. These characteristics include: Particle size distribution, aggregate crushing value, apparent saturated surface dry specific gravity, dry rodded bulk density and water absorption capacity. All the characterisation testing was done according to AS 2758.1 [19] and AS 1141. [20] Table 2 shows the particle size distribution. Table 3 shows the results of the tests to determine the other relevant characteristics.

At this stage, it is appropriate to show a comparison between this aggregate and three other types. These are the Granite natural aggregate, the Dacite natural aggregate, and another commercially available pelletized fly ash lightweight aggregate which will be referred to here as SP, standing for sintered and pelletized. The relevance of the Granite and Dacite aggregate is that these are the natural aggregates commonly used for good concrete production in this country and elsewhere. On the other hand, the SP aggregate is a sintered pelletized fly ash aggregate that has been a successful commercial lightweight aggregate since the 1960's. It is important to compare the qualities of the new product 'Flashag' to those of the existing and probably, so far, the most successful lightweight aggregate product that is derived from the same main ingredient, which is fly ash. Table 4 lists the properties of the three other main aggregates; namely Granite, Dacite and the SP lightweight aggregate.

Table 2- A Typical Sieve analysis of the Flashag aggregate

Sieve size	Mass retained g	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
13.20 mm	0	0	0	100
9.50 mm	371.8	18.6	18.6	81.4
6.70 mm	392.5	19.6	38.2	61.8
4.75 mm	222.1	11.1	49.3	50.7
2.36 mm	387.5	19.4	68.7	31.3
1.70 mm	97.9	4.9	73.6	26.4
1.18 mm	109.1	5.5	79.1	20.9
4.25 μm	170.8	8.6	87.7	12.3
300 μm	45.8	2.3	90	10
150 μm	76.7	3.8	93.8	6.2
<150 μm	123.0	6.2	100	---
Total	1997.2	100		

Table 3- Characteristics of the Flashag aggregate

Property	Series 1 Made from classified F ash	Series 2 Made from unscreened ash directly from collectors
	Value	Value
Apparent specific gravity based on saturated surface dry condition	1.69	1.59
Apparent specific gravity based on oven dry condition	1.61	1.55
Dry rodded bulk density	848 kg/m^3 (52 lb/ft^3)	862 kg/ m^3 (54 lb/ft^3)
Crushing value	28%	26%
Absorption capacity (in 24 hours)	3.4%	2.4%

Comparison between the properties of Flashag shown in Table 3 and those of Granite, Dacite and SP shown in Table 4, indicates that Flashag has a much less absorption capacity than SP. Moreover, the crushing value of Flashag is significantly less than that of SP. Thus it is expected that Flashag may produce concretes that are more durable and stronger than SP concretes and at the same time have comparable and more stable weight than SP.

Table 4- Properties of the three other main aggregates

Property	SP	Granite	Dacite
Apparent specific gravity based on saturated surface dry condition	1.72	2.77	2.51
Apparent specific gravity based on oven dry condition	1.4	2.74	2.50
Dry rodded bulk density	831 kg/m^3 (52 lb/ft^3)	1478 kg/m^3 (92 lb/ft^3)	------
Crushing value	35%	16.9%	15.5%
Absorption capacity (in 24 hours) for 12 mm coarse	8.5%	0.8%	0.54%
Absorption capacity (in 24 hours) for 6 mm coarse	8.5%	-------	------
Absorption capacity (in 24 hours) for 3mm coarse	8.5%	-------	-------
Absorption capacity (in 24 hours) for the fines	10.7%	2.7%	2.7%

CONCRETE PRODUCTION

Concrete mixtures were designed and tested for the fresh and hardened relevant characteristics. The mixtures' designs are shown in Tables 5 and 6. Table 5 relates to series 1 while Table 6 relates to series 2. The Tables show the proportions based on saturated and surface dry conditions of the aggregates. They also show the mixture design for the four types of concrete made for this study so that a direct comparison may be made between concretes from the four aggregates. The design was performed so that the concretes of the same series possess the same cement content and the same content of any pozzolanic materials that may be producing a cementitious effect. The amount of water was designed so as to achieve about the same workability as measured by the slump test. In series 1 the Flashag aggregate concrete had the highest water content and water-cement ratio. In series 2 all mixtures had exactly the same water content and water-cement ratio. The density of the fresh and compacted concrete was measured for the four types and the values are reported in Tables 5 (a) and 6 (a), and expressed in imperial units in Tables 5(b) and 6 (b). It is of particular importance to note that in both series, the Flashag mixtures used totally lightweight aggregates that included the fines.

Concretes of Series 1 were manufactured, cured and tested by the author and the technical staff at the University of New South Wales. Concretes of Series 2, however were manufactured, cured, tested and reported by the independent firm: Coffey Geosciences. The independent firm executed the mixes and testing according to the Australian Standards.

Table 5 - Concrete Mixture Design (Saturated and Surface Dry Aggregates Condition) for the Three Types of Aggregates Tested in Series 1. Quantities are per cubic metre of compacted concrete.

		Granite concrete	SP concrete	Flashag concrete
Cement	kg	300	300	300
Silica Fume	kg	40	40	40
Water	Litres	172	150	193
Water reducing agent	Litres	0.49	0.49	0.49
Superplasticiser	Litres	1.95	1.95	1.95
Natural coarse agrregate	kg	1001	0	0
Natural fine aggregate	kg	288	0	0
12 mm SP	kg	0	293	0
6 mm SP	kg	0	289	0
3 mm SP	kg	0	316	0
SP fines	kg	0	233	0
Coarse FLASHAG 12 mm	kg	0	0	255
Coarse FLASHAG 6 mm	kg	0	0	255
Coarse FLASHAG 3 mm	kg	0	0	256
FLASHAG fines	kg	0	0	162
Fly ash	kg	300	300	300
Water/ cement ratio		0.57	0.5	0.64

Table 6 - Concrete Mixture Design (Saturated and Surface Dry Aggregates Condition) for the Four Types of Aggregates. Series 2 (Mixed and Tested by the independent firm Coffey Geosciences at their premises). Quantities are per cubic metre of compacted concrete.

		Granite concrete	SP concrete	Dacite concrete	Flashag concrete
Cement	kg	370	370	370	370
Silica Fume	kg	56.92	56.92	56.92	56.92
Water	Litres	207.2	207.2	207.2	207.2
Water reducing agent	Litres	2.96	2.96	2.96	2.96
Superplasticiser	Litres	1.43	2.85	0.71	0.00
Natural coarse agrregate	kg	893.7	------	820	------
Natural fine aggregate	kg	626.3	------	626.3	------
12 mm to 3 mm Coarse SP	kg	-------	481.4	------	------
SP fines	kg	-------	475.5	------	------
Coarse FLASHAG 12 mm to 3 mm	kg	-------	------	------	440.4
FLASHAG fines	kg	-------	------	------	510.6
Fly ash	kg	142.3	142.3	142.3	142.3
Water/ cement ratio		0.56	0.56	0.56	0.56
Water/cementitious materials ratio		0.36	0.36	0.36	0.36

Table 5 (b) - Concrete Mixture Design (Saturated and Surface Dry Aggregates Condition) for the Three Types of Aggregates tested in series 1. Quantities are per cubic yard of compacted concrete.

		Granite concrete	SP concrete	Flashag concrete
Cement	lb	504.6	504.6	504.6
Silica Fume	lb	67.3	67.3	67.3
Water	lb	289.3	252.3	324.6
Water reducing agent	fl oz	13	13	13
Superplasticiser	fl oz	52.5	52.5	52.5
Natural coarse agrregate	lb	1684	0	0
Natural fine aggregate	lb	484	0	0
12 mm SP	lb	0	493	0
6 mm SP	lb	0	486	0
3 mm SP	lb	0	531.5	0
SP fines	lb	0	392	0
Coarse FLASHAG 12 mm	lb	0	0	429
Coarse FLASHAG 6 mm	lb	0	0	429
Coarse FLASHAG 3 mm	lb	0	0	431
FLASHAG fines	lb	0	0	272
Fly ash	lb	504.6	504.6	504.6
Water/ cement ratio		0.57	0.5	0.64

Table 6 (b) - Concrete Mixture Design (Saturated and Surface Dry Aggregates Condition) for the Four Types of Aggregates. Series 2 (Mixed and Tested by the independent firm Coffey Geosciences at their premises). Quantities are per cubic yard of compacted concrete.

		Granite concrete	SP concrete	Dacite concrete	Flashag concrete
Cement	lb	622	622	622	622
Silica Fume	lb	96	96	96	96
Water	lb	348.5	348.5	348.5	348.5
Water reducing agent	fl oz	80	80	80	80
Superplasticiser	fl oz	38.5	76.7	19	0.00
Natural coarse agrregate	lb	1503.2	------	1379.2	------
Natural fine aggregate	lb	1053.4	------	1053.4	------
12 mm to 3 mm Coarse SP	lb	-------	809.7	------	------
SP fines	lb	-------	799.8	------	------
Coarse FLASHAG 12 mm to 3 mm	lb	-------	------	------	740.8
FLASHAG fines	lb	-------	------	------	858.8
Fly ash	lb	239.3	239.3	239.3	239.3
Water/ cement ratio		0.56	0.56	0.56	0.56
Water/cementitious materials ratio		0.36	0.36	0.36	0.36

PROPERTIES OF THE FRESH AND HARDENED CONCRETES

The three types of concrete tested in series 1 had very similar workability conditions. In series 1, the slump was very low for the three types. The three types, however, were workable, easily compactable and did not exhibit segregation or bleeding. The hardened concretes were tested at the ages of 7 and 28 days. The results are recorded in Table 7. At 7 days, only the compressive strength was determined. It is observed that the value of the compressive strength of Flashag aggregate concrete is substantially higher than that of the corresponding mix made from the SP lightweight aggregate. What is even more remarkable is that the strength of the Flashag aggregate concrete at this early age is higher than the strength of the normal weight aggregate concrete made with Granite aggregates. This is in spite of the fact that the Granite aggregate concrete is nearly 20% heavier than the Flashag aggregate concrete. Moreover, the apparent porosity, which is an indicative of surface permeability, is much lower in Flashag concrete than in both SP and Granite concretes. This characteristic indicates that the Flashag concrete is probably more resistant to adverse environmental conditions than the previously known fly ash based SP concrete and the normal weight Granite concrete.

Table 7 - Properties of Fresh and Hardened Concretes from the Three Types of Aggregates- Series No. 1

Property	Granite Concrete	SP Concrete	Flashag Concrete
Slump	3 mm (0.12 in)	3 mm (0.12 in)	2 mm(0.1 in)
Fresh density, kg/m^3 (lb/ft^3)	2232 (139)	1722 (108)	1800 (112)
Air dry density, kg/m^3 (lb/ft^3)	2180 (136)	1602 (100)	1780 (111)
Oven dry density, kg/m^3 (lb/ft^3)	2134 (133)	1540 (96)	1747 (109)
Apparent porosity	4.5%	13.3%	3.1%
7 day compressive strength, MPa (psi)	36.3 (5263)	28.4 (4118)	38.8 (5626)
28 day compressive strength, MPa (psi)	56.3 (8163)	44.6 (6467)	62.9 (9121)
28 day modulus of elasticity, GPa (psi)	32.5 (4712.5×10^3)	16.7 (2421.5×10^3)	23.7 (3436.5×10^3)

At the age of 28 days, the compressive strength and modulus of elasticity values were determined. The 28 day compressive strength of Flashag concrete is 62.9 MPa, which is comfortably classified as high strength concrete. The compressive strength recorded for SP concrete was 44.6 MPa, and the value for the normal weight Granite concrete was 56.3 MPa. Thus Flashag concrete is clearly and consistently superior to both other types of concretes in its compressive strength.

The author has also measured the modulus of elasticity by the method of strain controlled loading. [17,21] The results showed that the modulus of elasticity value for Flashag concrete is 23.7 GPa while that for SP concrete is 16.7 GPa and for Granite aggregate concrete is 32.5 GPa. It is expected that lightweight concrete would possess a lower value of elasticity modulus. This is because the modulus of elasticity depends primarily on that of the aggregates. Flashag concrete has a significantly higher modulus of elasticity than SP concrete. This indicates the higher stiffness value of the Flashag aggregate when compared to SP aggregate. The value of the elastic modulus for Flashag is expectedly lower than that of normal weight Granite concrete. This is by no means an undesirable characteristic because a lower E value allows larger deflections in the case of vibrations or earthquake occurrences, thus providing more ductility to the structure. On the other hand, this value should not be too low as to cause very large deflections in normal service conditions. The value recorded for Flashag is in between that of SP and Granite concretes. Thus it is indicative of better serviceability than SP concrete structure and enhanced ductility over a similar structure made from Granite concrete.

Results from series 2 are shown in Table 8. The concrete mixtures of this series possessed medium slump value and had excellent workability and compactability characteristics. Again, the results obtained in series 1 were confirmed by those of series 2. The 7 day and the 28 day strength values were consistently higher than the values for SP concrete and also higher than the values obtained for the natural aggregate concretes. Flashag concrete was 20% higher in compressive strength than the common Dacite aggregate concrete. It was also 14.6% stronger than Granite aggregate concrete. Flashag concrete was 25% stronger than the commercially available SP aggregate concrete. Moreover, tensile strength values showed similar trends of superior results from Flashag concrete. Again, the value of the modulus of elasticity of Flashag concrete was lower than that of Dacite or Granite concrete but higher than SP aggregate concrete.

Table 8 - Properties of Fresh and Hardened Concretes from the Four Types of Aggregates, Series 2 (mixed , executed and tested by the independent firm Coffey Geosciences at their premises).

Property	Granite Concrete	Dacite Concrete	SP Concrete	Flashag Concrete
Slump mm	75 (3 in)	75 (3 in)	85 (3.35 in)	85 (3.35 in)
Measured air content %	2	2.1	6.2	3.8
Fresh density, kg/m^3 (lb/ft^3)	2260 (141)	2280 (142)	1770 (110)	1780 (111)
S.S Dry density, at 28 days, kg/m^3 (lb/ft^3)	2285 (143)	2290 (143)	1818 (114)	1815 (113)
7 day compressive strength, MPa (psi)	38.6 (5597)	37.4 (5423)	34.6 (5017)	40.75 (5909)
28 day compressive strength, MPa (psi)	58.25 (8446)	55.5 (8048)	53.4 (7743)	66.75 (9679)
28 day indirect tensile strength (psi)	3.55 (515)	3.45 (500)	3.70 (536)	3.75 (544)
35 day modulus of elasticity, MPa (psi)	32 500 (4712.5×10^3)	31 500 (4567.5×10^3)	19 000 (2755×10^3)	25 500 (3697.5×10^3)

DRYING SHRINKAGE PROPERTIES

The importance and effects of drying shrinkage in concrete structures can not be over-emphasized. [17, 22] Neville has indicated that lightweight aggregate usually results in higher shrinkage values mainly because of the lower modulus of elasticity of the aggregate. [23] Concrete practitioners pay a premium for the production of low shrinkage concrete whether by using low shrink Granite aggregates or low shrinkage cement. There has been a worry that the use of lightweight aggregate concrete may increase shrinkage deformation and cracking. Indeed there has been some evidence to this effect using certain lightweight aggregates. [24] When restrained, drying shrinkage causes cracking. Besides being unsightly, shrinkage cracking is a source of further deterioration due to the increased permeability to water and deleterious agents and subsequent deterioration due to freezing and thawing in cold regions. A low shrinkage concrete reduces the quantity of secondary reinforcement and thus can significantly reduce the cost of structures. It was therefore necessary to measure shrinkage values when using Flashag aggregate for concrete and compare the values with those of similar grade concretes from other aggregates. The shrinkage sampling and measurements were performed by an independent testing laboratory through Coffey Geoscience Pty Ltd and according to Australian Standards. [25] The Australian Standards differ from some other Standards in this test in that drying starts after only 7 days of curing in lime saturated water. Hence the results may appear larger than results obtained from following Standards that apply drying after 28 days of under lime saturated water curing. The results of the testing are shown in Table 9. These results clearly and consistently show that concrete manufactured with Flashag performed significantly and remarkably better than all the other concretes in this series. As expected, however, the largest shrinkage was recorded for the SP aggregate concrete. The Dacite aggregate concrete, which is the most commonly used concrete in Australia was only marginally better than the SP concrete. The Granite aggregate concrete also did not score a much better result. The factors that cause this result are discussed in more detail in the following section.

Table 9 - Shrinkage Properties of Fresh and Hardened Concretes from the Four Types of Aggregates, Series 2 (mixed , executed and tested by the independent firm Coffey Geoscience, at their premises)

	Shrinkage value (microstrain)			
Days of Drying	**Granite Concrete**	**Dacite Concrete**	**SP Concrete**	**Flashag Concrete**
7	590	570	550	400
14	730	740	770	520
21	770	790	820	540
28	810	800	840	560
56	850	880	890	590

PERFORMANCE OF FLASHAG IN CONCRETE

The superior performance of Flashag concrete as far as strength and shrinkage are concerned may be understood when a closer look is given to the nature of the individual Flashag aggregate. Figure1 shows the major types of aggregates used in this study. The Flashag lightweight aggregates, shown on the left of the photograph are angular. The aggregates shown in the middle are Granite. These are irregular but have a smooth texture. The aggregates on the right of the photograph are those of the SP lightweight variety. These are round and smooth as a result of the pelletizing during their manufacturing procedure.

Figure 1. Flashag (on the left), Granite (in middle) and SP aggregates

The process of manufacturing the Flashag aggregates results in deliberately creating a surface that is dominated by very small 'crators'. These are not continuous pores but have originated from tiny bubbles that were dispersed into the body of the aggregate during its manufacture. Figure 2 shows these 'crators' on the surface of an aggregate.

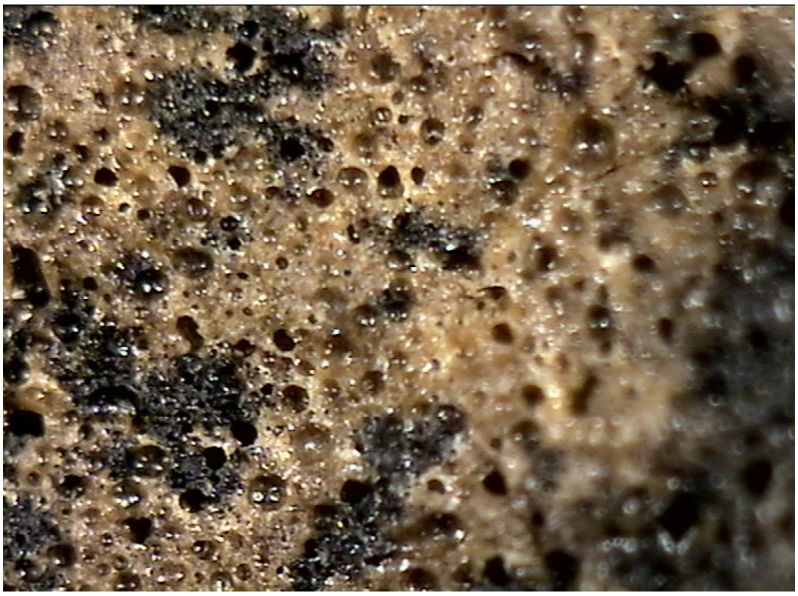

Figure 2. A closeup of Flashag aggregate surface (representing approximately 3 mm)

This crator-like formation is essential for the function and efficacy of the aggregates. In the concrete, they act to enhance the adhesive and mechanical bonding between the matrix and the aggregate. The strong bond that results is vital in the increased concrete strength. In normal weight aggregate concrete, the weakest area is the interfacial zone, which is the first to fail and act as a crack propagator. This is evident in Figure 3 which shows a failure surface of a Dacite aggregate concrete. The failure line is an extension of the de-bonded aggregate–matrix interface. The interface is clearly separated from the hardened cement paste. Thus, in spite of the actual strength of the aggregate itself, and that of the hardened paste, it is the weak interface that in effect limits the strength of the composite.

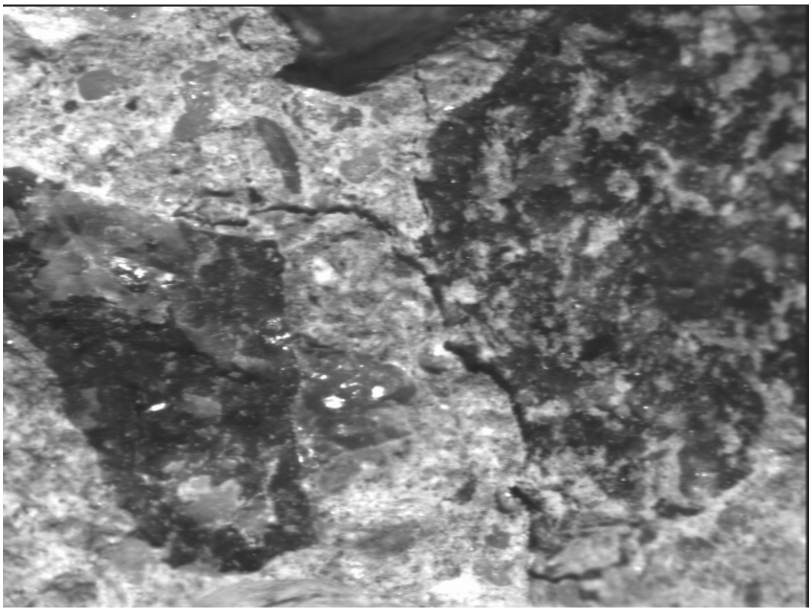

Figure 3. Fracture surface in Dacite aggregate concrete

In contrast, the bond between the Flashag aggregates and the matrix is strong. This is qualitatively demonstrated in Figures 4 and 5 which show a Flashag aggregates embedded in the matrix of concrete and exposed after a cylinder crushing test. The interface zone is evidently in tight and locking bond between the two phases of the concrete. Cracking did not initiate in the interface but rather was arrested at the interfacial zone. This means that cracks that may occur in the aggregate itself did not spread uncontrollably through the matrix. This is due to both the strength of the interfacial zone and the strength of the matrix itself. The resistance of Flashag concrete to shrinkage can also be attributed to the same effects. The tight interlocking between the Flashag aggregate and the cement paste matrix causes little internal slippage and therefore smaller strains.

Figure 4. Fracture surface in Flashag aggregate concrete

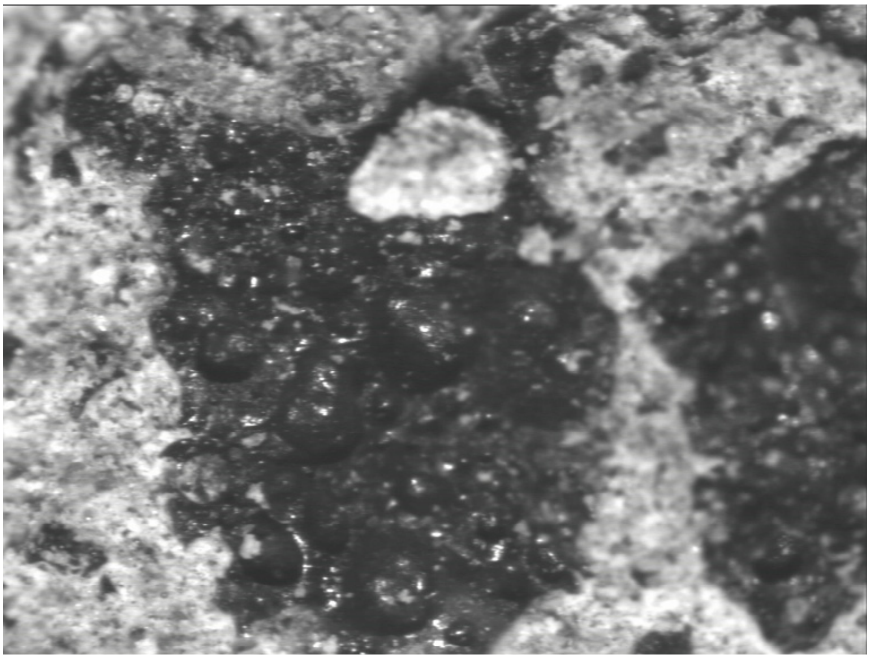

Figure 5. Interlock between the Flashag aggregate and the matrix

CONCLUSIONS

A new lightweight aggregate suitable for the use in concrete production has been manufactured. Important properties of these aggregates have been tested and found to be superior to those of previously known pelletized type. The concrete made with Flashag aggregates was 25% stronger than that made with the best of fly ash based lightweight aggregates that are currently available. Further, the strength of the lightweight concrete manufactured with Flashag aggregates is found to be superior to the traditional normal weight concrete by 20%. High strength structural concrete in the order of 67 MPa (9715 psi) strength was obtained with 370 kg of cement in the cubic metre (622 lb/yd^3). A compressive strength of 63 MPa (9135 psi)was obtained with a mixture containing 300 kg of portland cement in the cubic metre (504.6 lb/yd^3) of Flashag aggregate concrete. The resulting concrete had a density that is 22% less than normal weight concrete. Drying shrinkage of concrete made with Flashag aggregates was 33% less than normal weight concrete. Porosity of the Flashag concrete was significantly less than that of normal weight concrete, indicating lower permeability and a better durability potential. High strength lightweight durable concrete that consumes less Portland cement than normal weight concrete is now easily produced. The patented technology of manufacturing Flashag is simpler, potentially much cheaper, and more consistent than other available technology that has been used in the manufacture of aggregates from fly ash or other sources. The ash used to manufacture the aggregates can be retrieved directly from the ash collectors without further screening or classification. The environmental advantages added to the evident economical and functional advantages to the building industry indicate that this new aggregate is promising a great success.

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