Fracture characteristics of High-Strength Light-Weight Cement Mortar Composites reinforced with the waste products of alluminium processing

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ABSTRACT: An investigation was carried out to summarize the results of the mechanical properties of high strength lightweight eloxal reinforced cement mortar subject to short term loads. Eloxal (in the solid slag form) is a waste obtained during the production of aluminum. It is mainly of aluminum oxide, SiO_2, CaO, MgO and other substances. It's a hard substance, having sufficient strength with additive properties and bonds very rapidly. Eloxal reinforced cement mortars in the present investigation are tested for their compression and fracture behavior. Data were obtained pertaining to compressive strength, fracture behavior (using dogbone tension tests and double cantilever beam tests), role of moisture and drying effects. Deformation properties under load were studied to provide insight into the internal behavior and failure mechanism of light weight eloxal reinforced cement mortar. To analyze the mode of failure, distribution of eloxal particles in cement mortar and the deformation behavior, several optical and Scanning Electron Microscope (SEM) photographs were taken to study the mechanism. Results of the tests of eloxal reinforced cement mortar are compared with unreinforced cement mortar and information obtained else where in earlier tests of normal weight cement mortar. Structural composites materials offer an excellent opportunity to produce components that achieve weight savings and improved structural properties. The eloxal particles (dispersoid) added to cement mortar in the present investigation is varied from 20 to 40 wt%. in steps of 10 wt.%. The resulting composite blocks cast were tested for their properties.

1 INTRODUCTION

Lightweight cement mortar has been used successfully for many years for structural members and systems in buildings and bridges. One of the earliest applications in North America was in the construction of cement mortar ships during World War I (C. Wilson). Through the years, by judicious selection of the lightweight aggregate and careful proportioning, semi-lightweight cement mortars having high compressive strengths have been made (B.H. Spratt). Although such strength is not necessary in many structural applications, there are advantages to the use of very high strength lightweight concrete in such applications as offshore drilling platforms. Such concrete has greater buoyancy and thus is easier to tow in shallow waters, and less excavation is required in construction of the dry dock compared to heavier structures. There is one instance where such cement concrete have been used for oil drilling platforms in the Arctic (G. Wischers and W. Manns). In addition to its lighter weight, which permits savings in dead load and so reduces the cost of both super structure and foundations, this cement concrete is more resistant to fire and provides better heat and sound insulation than cement mortar of normal density (R.L. Carrasquillo, J.J. Shideler and J.A. Hanson). For lightweight cement mortar structures, as for structures of normal weight cement concrete, there is a well-established trend toward using higher compressive strengths. This permits the use of smaller member sizes, which in turn permits further reduction in dead load with attendant cost savings, and extends the practical range of span as well (P.H. Kaar, P.T. Wang and R.L. Carrasquillo).

Little useful information has been available to the structural engineer on the engineering properties of high-strength lightweight cement mortar. The main purposes of the work described in this paper were a) to gain insight into the difference in the internal behavior of high-strength light weight cement mortar compared with normal cement mortar and b) to establish its mechanical properties and compare these with the properties of cement mortar of normal density. The work of this paper is aimed at establishing the fracture characteristics of eloxal particles to the one by the author of this paper for the fracture study of chilled aluminum alloy-quartz particulate composite (Joel Hemanth). The salient feature of this model is the presence of a zone, called the pseudoplastic zone, in which the aluminum matrix is cracked, but reinforcing fibers continue to provide resistance to the crack opening. Such a behavior requires use of a test specimen allowing sufficient length of crack development in order that a complete crack resistance and estimate of the fracture toughness may be obtained.

Advanced composite materials such as fiber-reinforced polymers have the potential to revolutionize engineering technology. In order to use these advanced composite materials, a detailed knowledge of their mechanical behavior is imperative. Moreover, structurally efficient design using these advanced composites mandates a detailed knowledge of their mechanical properties. The mechanical properties of composites have received much attention for decades, but their performance in environments simulating hostile service and their long-term durability are only beginning to be studied. These composites are particularly suitable because they are lightweight, presumably durable, corrosion resistant and have high compression strength. Their lower density is important not only because it adds less weight to the existing structures but also because it is very important during construction. Heavy equipment is needed for construction with steel; however, it is not needed for lightweight composites. The fact that these composites are electrically non-conductive and have impact resistance also helps in certain applications. Extensive research has been carried out on using these composites for strengthening; however, information about their durability is still lacking (Y. Xiao, T.Harmon, P.Labossier, A.Nanni and H. Toutanji). Eloxal, the waste is obtained during the production of aluminum in the plant produced by means of electrolysis or limited oxidation processing of metal plates in the electrolyte solution. The present composite developed using eloxal as the dispersoid has the properties of rapid hardening, light weight, high sulphate resistance, low thermal coefficient of expansion along with good mechanical properties (J. Piasta and A.N.Scian).

2 EXPERIMENTAL PROCEDURE

2.1 *Composition of the matrix material and the dispersoid*

Chemical composition of the matrix (cement mortar) is given in Table-1.

Table 1. Chemical composition of the Cement (Birla super 53 Grade, normal portland cement, ASTM type I).

S_iO_2	CaO	Al_2O_3	Fe_2O_3	MgO
22.02	62.26	3.99	2.26	3.30

(Balance of the composition contains SO_3, Na_2O and K_2O)

In this investigation eloxal particles from 20 to 40 wt.% in steps of 10 wt.% were dispersed in the matrix. Chemical composition and some properties of eloxal (dispersoid) are as follows: Density: 1.3 gm/cc, Hardness: BHN 310, Melting point: 680 ^oC and Youngs Modulus 75 GPa, Size distribution of the dispersoid: 3.72 to 7.8 mm, Chemical composition of the dispersiod is indicated in Table 2.

Eloxal available from aluminum industry will be in the form of a hard solid slag and this is reduced to the required size into the granular form using a ball mill. Before adding, eloxal was prepared by washing it with water and thus the soluble NaOH and other substances were removed. Finally the solid eloxal was dried in an oven at 105 ^0C for 2 hours.

Table 2. Chemical composition of the dispersoid (eloxal).

Al_2O_3	S_iO_2	MgO	CaO	Na_2O
48.21	29.82	3.32	15.83	1.21

(Balance of the composition contains Al-Hydroxide)

2.2 *Mix Proportions and Casting Procedure*

The cement-aggregate ratios and water-cement ratios used in the present investigation were 1:3 respectively. The aggregate grading is shown in Table 3.

Table 3. Sand aggregate gradation.

Passing Sieve no.	Retained Sieve no.	Aggregate size (mm)	% Proportion
8	16	1.18 – 2.37	16
16	30	0.7 – 1.19	30
30	50	0.3 – 0.6	40
50	100	0.15 – 0.3	10
100	Pan	Less than 0.15	5

Normal portland cement (by Birla, India) ASTM Type 1, was used. The casting procedure consists of mixing dry, predetermined quantities of fine graded aggregate and cement for about three minutes. Water was then added slowly and the mixing continued for another minute. Dry eloxal particles (size 3.72 to 7.8 mm) were slowly and continuously added as the mixing continued. Mixing was done by a medium sized Hobart mixing machine of planetary mixing action was used. The resulting mix was used to prepare compression (152*305 mm cylinders, ASTM C 109 standards), tension (dogbone tension test specimen with a notch) and Double Cantilever Beam (DCB) testing specimens. Finally the prepared specimens were compacted and leveled and left to cure. The specimens were de-molded after 24 hours and moist cured in a water bath at room temperature for 7, 14, 21 28, 35 and 42 days before testing. A series of four cement mortar mixtures were made, containing 20%, 30% and 40% eloxal particles (dispersoid) respectively.

2.3 *The Notched Tensile Specimen (NTS) testing and Double Cantilever Beam (DCB) Testing*

Direct tension test on the notched specimens were performed in an Instron machine . The dogbone tension test specimen of 175 mm effective length with right angled notch 3 mm deep cast on opposite sides to resist the crack in one plane was used in the present investigation. The casting procedure, mixes and curing history were identical to those used for DCB specimens. Similar to DCB testing, a tensile load of 2.0 KN and cross head speed of 2 mm per minute were used in the tests. An extensometer to measure the displacement at the notch was fixed on the specimen, each arm a distance of 25 mm from the notch.

The dimensions of the Double Cantilever Beam (DCB) specimen used in this study were adopted according to findings available elsewhere (K. Visalvanich). On each side of the specimen, a groove was cast which was 12.7 mm wide at the surface and 7.6 mm deep before sloping into an apex angle of 60 degrees. To prevent the crack from deviating from the assigned path along the groove, two 2 mm diameter plain steel wires, placed as close to the groove as possible, were used to reinforce each arm of the beam. The initial notch depth was constant throughout the experiments and set at 101.6 mm. The mould was made such that the cement mortar could be cast in a horizontal position. Each cover had a pre-molded notch attached to it, to produce the side grooves in the specimen. On the bottom cover was also attached a removable pre-molded notch to produce the required initial notch in the specimen.

The DCB specimens were tested in an Instron machine in vertical position, the vertical load being transmitted to the arms through a loading wedge and a roller bearing system. Details of wedge and roller bearing system may be found in other findings (Y.N. Zibra).

The full load cell scale chosen for the DCB specimen testing was 2 KN and a crosshead speed of 2 mm/min was used throughout the investigation. An extensometer with a range of 25 mm was used to measure the Arm Opening Displacement (AOD). The arms of the extensometer attached to the axles of the roller bearings by small screws. The signal from the extensometer was amplified by the strain data unit and used to control the chart servo-drive mechanism. This way, the crack mouth displacement and the load could be plotted as the abscissa and ordinate, respectively, on am X-Y recorder. Calibration of the extensometer, carried out at the beginning of each test, was done with the help of a micrometer screw gauge having an accuracy of 10^{-3} mm. Crack lengths were observed and measured through a vertical axis traveling microscope with an accuracy of ± 0.1 mm. The specimen was loaded at a rate of 2 mm per minute until crack extension was observed to occur after which the specimen was unloaded at the same rate, having noted the crack length at which the crack began to extend. This process of loading and unloading was repeated until the crack length was developed to the zero zone or until the specimen failed. The process of loading and unloading eliminates the influence of permanent deformation on the compliance of the DCB specimen.

Microscopic examination was conducted on the specimens using a Scanning Electron Microscope (SEM) and the optical microscope (Neophot–21) under different magnifications to study the distribution, orientation, bonding of eloxal particles in cement mortar and the mode of fracture.

3 RESEARCH SIGNIFICANCE

The research shows that high-strength lightweight cement mortar possesses properties that are significantly different form normal cement mortar and also different from high-strength normal weight cement mortar. Such cement mortar as used in this investigation can be used in buildings and bridges mainly to reduce dead load and increase the practical range of spans. Eloxal in the form of scrap which is cheaply and abundantly available can be recycled to produce cement mortar-eloxal light weight and high strength composite. Thus, this paper provides important new information on the behavior and engineering properties of this material.

4 RESULTS AND DISCUSSION

Results of the micro and macro examination indicate that the shape of pores present, distribution and orientation of eloxal particles determines the mechanical properties of the composite developed. It is observed in the present investigation that, the maximum mechanical properties are obtained for composites containing 40% dispersoid and hence the discussion is based on this composition.

4.1 *Effect of Adding Eloxal to Cement Mortar*

The effect of adding eloxal to cement mortar as a dispersoid is that, the setting times of the mixture is gradually decreased and the strength is increased as compared against other cement composites. Microstructural studies reveal that, this decreasing effect of setting time and increase in the strength are attributed to solving of eloxal near the boundary boundray (between eloxal and cement mortar) forming ettringite and hydrogranate ($3Ca(Fe_2O_3, Al_2O_3, H_2O)$ phase, calcium aluminate hydrates and calcium silicate hydrates that occurs by reaction of cement mortar and eloxal, which forms a strong bond between the two (matrix and the dispersoid). The setting time of all cement mortar – eloxal mixes is in accordance with Indian Standards (IS) limits. SEM photograph (Fig. 1) shows the structure which contains calcium silicates (fibrous phase), portlandite [$Ca(OH)_2$], ettringite (dimple form) and hydrogranate phase (dark phase) (A. Benthur).

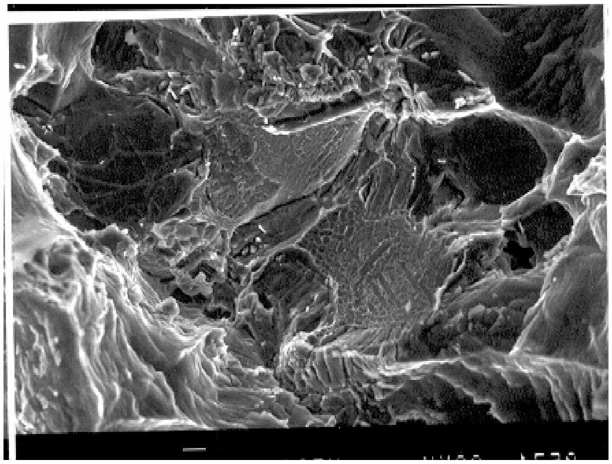

Figure-1. SEM photograph showing the microstructure of composite containing different phases (dispersoid content 40%).

Results of the microstructural analysis also supports that, hydration yields a white cover appearance and thus the main structure was formed as a growth of calcium hydroxide and hydrogranate phase among calcium silicate hydrate gels. A summary of the mechanical properties of the composite developed are indicated in table 4.

Table 4. Summary of mechanical properties of the composite.

% Dispersoid	Compression Strength, MPa (152*305mm cylinders)			Splitting Tensile Strength (MPa) of 152*305 mm cylinders (42 days)
	Days			
	28	35	42	
00	32.1	41.8	50.2	2.8
20	49.2	56.6	60.3	3.9
30	49.8	58.2	62.7	3.7
40	52.7	56.2	68.9	3.3

4.2 *Fracture Characteristics of the Composite*

A typical stress-deformation plot of one NTS specimen (containing 40wt.% dispersoid) is shown in Fig. 2.

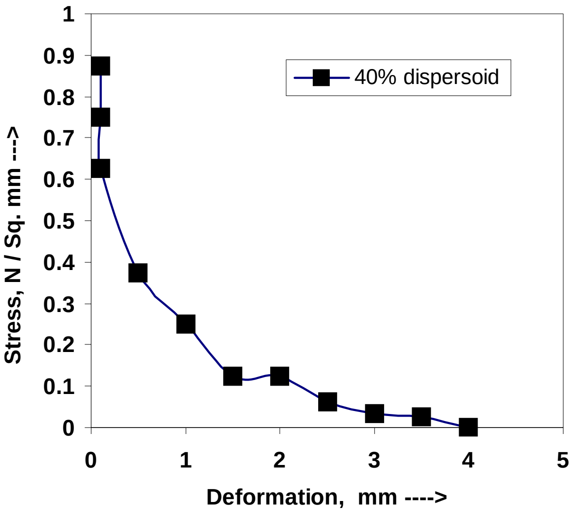

Figure 2. Stress-deformation plot of NTS specimen containing 40% dispersoid.

Fracture of cement mortar reinforced with eloxal particles can be adequately determined using a stress release law that can be observed form the dispersoid pullout curve of the notched dogbone specimens during the tension testing. SEM analysis reveals that the crack opening of the eloxal particles (dispersoid) reinforced in cement mortar depends on its volume and orientation. Microstructural studies also reveal that the shape of the dispersoid and its distribution in the test specimen greatly affect the fracture behavior. It is observed form Fig. 3 (Fracture energy with crack extension curve) that, the crack opening at which dispersoid offer no resistance to pullout is relatively small. This means that steady state crack propagation may be expected to occur at shorter crack lengths. SEM analysis shows that, failure response of all the DCB specimens tested was stable one throughout the test expect for a couple of specimens where a series of cracks were developed due to mis-orientation of eloxal particles.

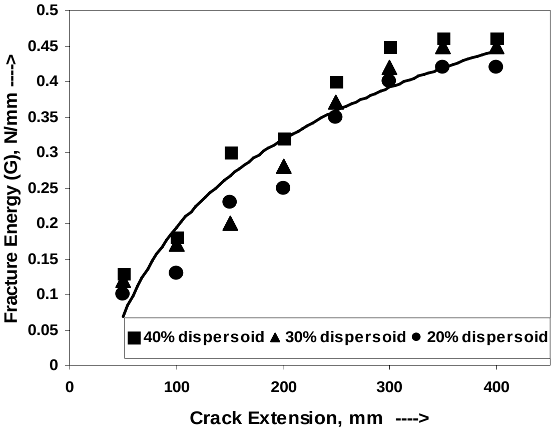

Figure 3. Plot of fracture energy Vs crack extension.

The mechanisms which control the fracture of the composite are dependent upon both microstructure and the deformation. The manner in which the stress response varies is an important feature of the fracture process. The stress required for cracking the specimen provides an useful information pertaining to the mechanical stability of the intrinsic microstructural features during straining and coupled with an ability of the material to distribute the strain over the entire volume are key factors governing the fracture of the composite. It is observed in the present investigation that the eloxal content of the composite is the most significant factor that affects fracture. Further, it is observed that, the eloxal content beyond 30 % by wt., the fracture energy values register a decreasing trend. The possible micro-mechanisms controlling the fracture behavior during loading are ascribed to the following synergistic influences.

a) Load transfer between the cement mortar matrix and the hard and brittle eloxal particle reinforcement.
b) Hardening arising from constrained deformation and triaxibility in the cement mortar matrix due to the presence of the brittle eloxal reinforcements. As a direct result of the particles resisting the deformation of the matrix, an average internal stress or back stress is created.
c) Residual stresses are also generated in the matrix (cement mortar) due to mismatch of eloxal particles.

During deformation it seems possible that the mismatch that exist between the brittle reinforcing particle and the matrix favors concentration of stress at and near the particle/matrix interface, causing the matrix in the immediate vicinity to fail permanently or the particle to separate from the matrix.

Conversely, fracture of the unreinforced composite on the microscopic scale, exhibited limited fracture energy and the fracture is brittle (Fig.4) and is normal to the major stress axis. Thus the presence of eloxal in the composite as the reinforcement has a pronounced effect on the fracture.

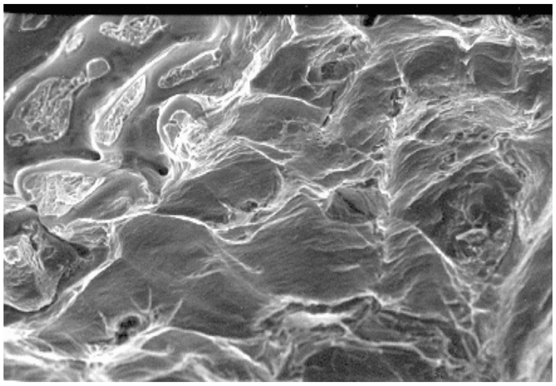

Figure 4. SEM structure of fractured surface of unreinforced composite.

4.3 *Microsrtuctural observation of the composite*

Optical microstructural studies (Fig. 5) reveal good bonding and distribution of eloxal particles throughout the matrix (cement mortar) with non-affective interfacial reaction. This may be one of the reasons for increase in strength and soundness of the composite developed.

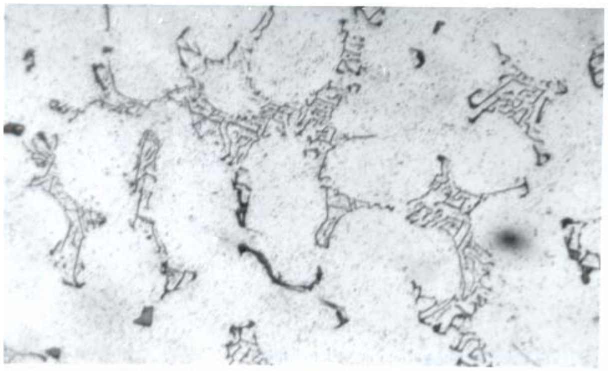

Figure 5.Optical microstructure of the composite containing 40% dispersoid.

Examination of the fracture surface features in the SEM indicate that, specimens at low magnification to identify the final fracture regions, and at higher magnification to identify regions of micro-crack initiation, early crack growth and final scale fracture features. Fracture surfaces revealed different topographics for the composite containing different weight percent of eloxal particles. Fracture of the composites containing 20% dispersoid on macroscopic and microscopic scales exhibited brittle fracture with isolated cracks in the matrix (Fig. 6).

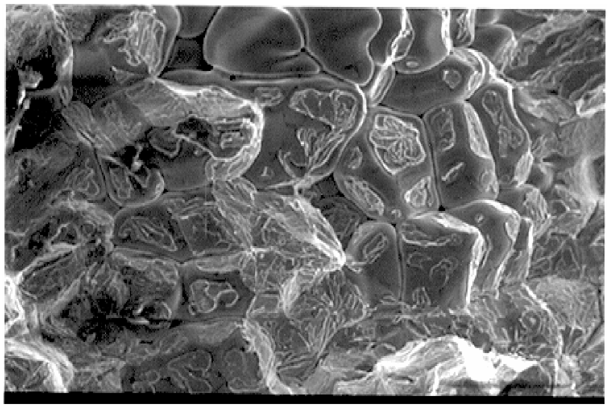

Figure 6. SEM structure of fractured surface of composite containing 20% dispersoid

Observations of the composite containing 40% dispersoid revealed large areas of the fracture surface to be covered with a bimodal distribution of dimples, which is an indication of the mixed mode fracture (Fig. 7). However growth of the void is limited by competing and synergistic influence of reinforcing eloxal particles and in the composite microstructure.

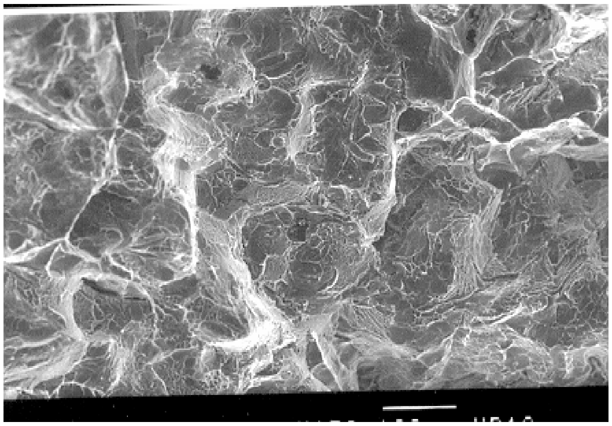

Figure 7. SEM structure of fractured surface of composite containing 40% dispersoid.

5 CONCLUSIONS

The following conclusions are drawn based on the experimental results presented.

1. Microstructural studies reveal good bonding and distribution of eloxal throughout the matrix without any interfacial reaction. This is one of the reasons for increase in the strength of the composite.
2. High strengths can be achieved with various admixtures of minerals but the use of eloxal as the dispersoid is mandatory to obtain light weight and high strength cement mortar composite.
3. The high strength light weight cement mortar composite investigated has satisfactory resistance to cyclic loading and this is conveniently studied from the tensile tests of notched dog-bone specimens.
4. The major mechanism that controls the fracture characteristics of the composite are the load transfer between cement mortar (matrix) and the hard eloxal particle (dispersoid).
5. The composite developed exhibited steady state crack propagation at shorter crack lengths.

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