

Processing and characterization of a lightweight concrete using cenospheres

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A study has been conducted in which a lightweight concrete was processed using ceramic microspheres, known as *cenospheres*, as a primary aggregate. The mechanical properties, including compressive strength, tensile strength, flexural strength and fracture toughness, were tested and cataloged. It was determined that the addition of high volumes of cenospheres significantly lowered the density of concrete but was also responsible for some strength loss. This strength loss was recovered by improving the interfacial strength between the cenospheres and the cement. The interfacial properties were quantified using interfacial fracture mechanics techniques. These techniques were also employed to find a suitable surface modifier with which to improve this interface. The admixture silica fume and the coupling agent Silane™ were found to be suitable candidates and both performed well in small-scale compression testing. Silica fume was eventually isolated as a prime candidate. The concrete produced with this admixture was tested and compared to a concrete with an equal volume fraction of cenospheres. The addition of silica fume improved the compressive strength of cenosphere concrete by 80%, tensile strength by 35%, flexural strength by 60% and fracture toughness by 41%.

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1. Introduction

This study presents how a new type of lightweight concrete was developed using ceramic microspheres as a primary aggregate. These ceramic microspheres are a waste product, so they are relatively inexpensive and the use of them has the added benefit of decreasing the strain on the environment. This aggregate allowed the density to be reduced significantly but initially caused some strength loss. The strength was later regained with the use of interface modifiers. The result is a high-performance lightweight concrete.

Concrete is the number one structural material used in the world today. The demand to make this material lighter has been the subject of study that has challenged scientists and engineers alike. The challenge in making a lightweight concrete is decreasing the density while maintaining strength and without adversely affecting cost. Introducing new aggregates into the mix design is a common way to lower a concrete's density. Normal concrete contains four components, cement, rock, sand and water. The rock and sand are the components that are usually replaced with lightweight aggregates.

Many studies have been done with a wide range of fillers with the purpose of developing a lightweight concrete. Many of these studies used organic fillers in order to decrease the density. Aziz *et al.* [1] studied the effects of cork granules. Slate used coconut fibers, all with little benefit [2].

In recent years work has been carried out documenting the details of inorganic admixtures, such as flyash, and today flyash is widely used in the concrete industry. Flyash is inexpensive, has good pozzolanic properties (reacts with water to form cementitious materials), and can be half the density of cement. Naik *et al.* has shown that flyash can not only decrease the cost and density, but also make the concrete stronger, more durable and more resistant to corrosion [3].

Silica fume is another compound, which has been studied extensively and is used in concrete today. Tazawa *et al.* have shown that silica fume can improve concrete strength, durability and corrosion resistance [4].

An important by-product of flyash is *cenospheres*, relatively large (10–300 μm) thin-walled microspheres produced during flyash formation. Clayton and Back show that cenospheres are formed during the coal burning process by evolution of gas becoming trapped in a viscous molten glass matrix [5]. These cenospheres can be reclaimed from flyash readily and are relatively inexpensive as a bulk product. They are also considered a waste product, so any use of them decreases the strain on the environment. Wandell has suggested many uses for this material, including using them as fillers in polymers and concrete [6].

A light micrograph of cenospheres is shown in Fig. 1. These cenospheres have a low specific gravity, (approx.

TABLE I Concrete mix design for control batch B1

Cement (portland type II)	298 kg (658 lbs.)
Fine aggregate (Sand)	521 kg (1148 lbs.)
Coarse aggregate (19 mm)	645 kg (1423 lbs.)
Coarse aggregate (3.2 mm)	160 kg (355 lbs.)
Water (Represents a 0.44 water cement or w/c ratio)	132 kg (290 lbs.)

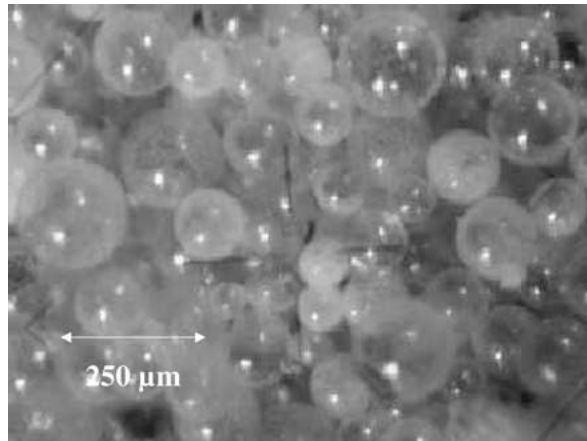


Figure 1 Light micrograph showing pure cenospheres (750 \times).

0.67) which makes them ideal to be used as a predominant aggregate in a lightweight concrete.

The purpose of this study was to develop a lightweight concrete using cenospheres and characterize the mechanical and fracture properties of this new material. The ability to tailor the properties of this new material through the use of interface modifications was also investigated.

Three concrete mixes were made based on a control mix seen in Table I. 50%, 75% and 100% of the fine aggregate were replaced in these mixes with cenospheres. All mechanical and fracture properties for these mixes were cataloged.

All properties in this study are reported as specific strengths in order account for the lowered density seen with the addition of cenospheres. This gives an idea of overall performance. The specific strength is per unit mass and can be converted to standard stress units by applying the measured bulk density given for each mix design.

Bimaterial fracture mechanics were employed to determine the interface properties of cenospheres and cement. These techniques have been recently used to characterize some materials [7, 8], but no such work has been done in the area of infrastructure materials like concrete. These tests quantitatively showed that the inherent weakness in cenosphere concrete is the cenosphere/cement interface. Interface modifier candidates were also found using this technique.

Small batches of concrete were mixed in order to further test interface modifier candidates. This was done to ensure that they would perform correctly under real world conditions. It was deemed necessary to test any potential interface modifier in a controlled and quick manner before investing the time and energy necessary to develop a large batch. These experiments showed that silica fume and a coupling agent called SilaneTM

had the best potential to improve the strength of the cenosphere concrete.

Silica fume was chosen as the best candidate to improve the performance of the cenosphere concrete due to its ease of use and low cost. A mix design was created incorporating this admixture and mixed on a large scale. All the mechanical and fracture properties of this material were investigated. These tests showed that all mechanical properties improved significantly with the addition of silica fume when compared to an equivalent concrete.

2. Experimental procedure and results

All of the following experiments were done in a controlled environment and according to ASTM standards when available. All values reported represent the mean of at least five experiments and the error is reported with 95% confidence.

2.1. Concrete mix design and specimen fabrication

All concretes used in this study were based on the Rhode Island Department of Transportation (RIDOT) Class XX AE. This mix design for one cubic yard of concrete can be seen in Table I.

The above recipe was our control batch (B1). The successive batches contained 20% (B2), 32% (B3) and 42% (B4) cenospheres by volume. These numbers represented 50%, 75% and 100%, respectively, of the sand volume that was replaced with cenospheres. This method was chosen to maintain a constant consistency insofar as one fine aggregate (sand) was always replaced with another fine aggregate (cenospheres).

All batches of concrete were mixed according to ASTM C192-95. The batches were allowed to harden for 24 hours and then placed in a wet bath and allowed to cure for 28 days before testing.

2.2. Density analysis

The density was recorded by measuring the weight of the cylindrical specimens, which had a known volume.

The density measurements for the different concrete batches can be seen in Fig. 2. As was expected, the density decrease was proportional to the amount of sand

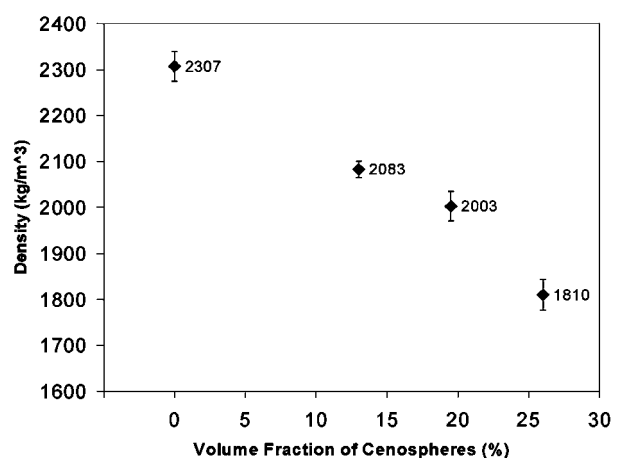


Figure 2 Density calculations for concretes with varying volume fractions of cenospheres.

replaced with cenospheres to a low value of approximately $1810 \pm 34 \text{ kg/m}^3$, 22% lower than the control batch density of $2307 \pm 32 \text{ kg/m}^3$.

2.3. Compressive strength

The compressive strength of the different concretes were measured according to ASTM C39-94. The specimen size used was 101.6 mm in diameter and 203.2 mm in height. These tests were performed on a Forney™ hydraulic testing system model FT-40.

The compressive strength for all batches of concrete can be seen in Fig. 3. The control batch B1 showed a specific compressive strength of $11.6 \pm 0.9 \text{ MPa/kg}$. When cenospheres were initially added in B2, there was a 30% drop in the compressive strength to $8.1 \pm 0.6 \text{ MPa/kg}$. B3 showed a minimal rise to $9.3 \pm 0.7 \text{ MPa/kg}$. B4 showed a specific strength of $6.7 \pm 0.7 \text{ MPa/kg}$, which represents a 42% drop in total specific compressive strength. It should be noted that all these concretes performed above the 20 MPa benchmark necessary for a structural concrete, but there is some loss in overall performance.

The mode of failure was also different for the cenosphere concrete. B1 showed a markedly shear type failure. The cenosphere concrete failed in a more violent way and almost always in a columnar fashion. One of

these samples can be seen in Fig. 4 next to a sample of B1. This is indicative of poor interfacial bonding between the cenospheres and the cement binder.

2.4. Tensile strength

The specific tensile strength of all specimens was measured according to ASTM C 496-96. These tests were also performed on a Forney™ FT-40 using the alignment jig suggested in the ASTM document to ensure that the load was applied perfectly along the diametral line. The specimen size was exactly the same as for compression testing.

The tensile strength for all batches can be seen in Fig. 5. B1 showed a specific tensile strength of $0.93 \pm 0.09 \text{ MPa/kg}$. When cenospheres were added in B2, there was a 35% drop in the tensile strength to $0.60 \pm 0.04 \text{ MPa/kg}$. There was a slight rise in the strength for B3 to $0.69 \pm 0.08 \text{ MPa/kg}$. B4 showed a tensile strength of $0.72 \pm 0.03 \text{ MPa/kg}$. This seems to imply that the tensile performance is lowered by the addition of cenospheres, but does not worsen as the amount of cenospheres increases.

Fig. 6 shows a tensile specimen of cenosphere concrete after failure. This figure shows the “popping out” of the coarse aggregate, which is not beneficial to the concrete due to the fact that the coarse aggregate is what gives concrete its strength. One would prefer to

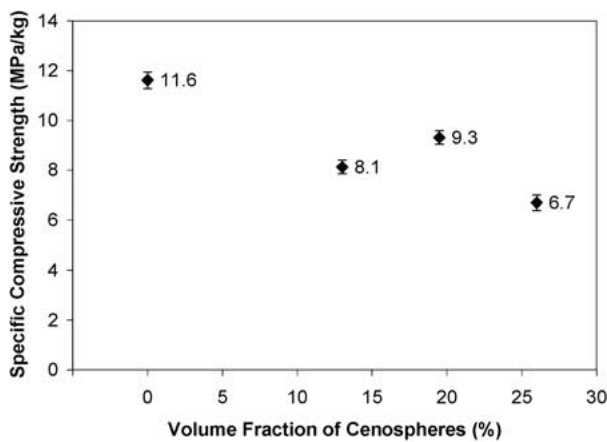


Figure 3 Specific compressive strength of concretes with varying volume fractions of cenospheres.

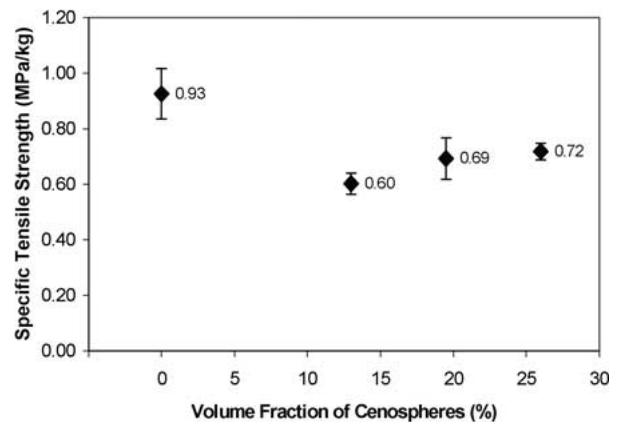


Figure 5 Specific tensile strength of concretes with varying volume fractions of cenospheres.

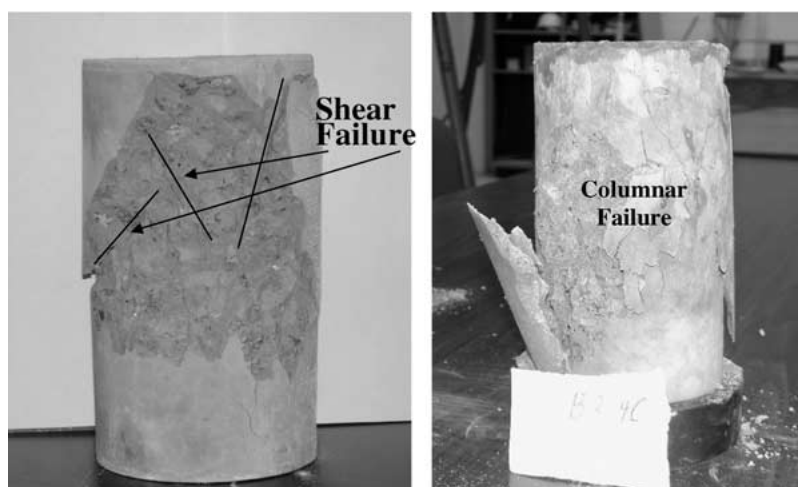


Figure 4 Normal failure mode for concrete (left) and failure mode of cenosphere concrete (right).

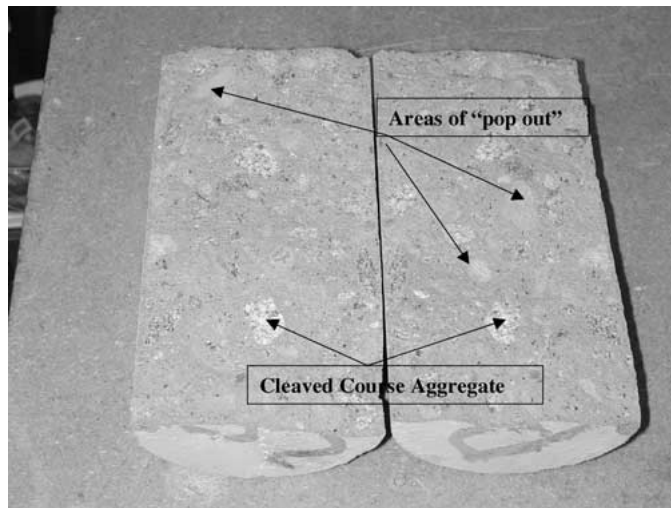


Figure 6 Tensile specimen showing both cleaved aggregate and “pop out”.

see more cleaving of coarse aggregate. This again is indicative of a poor cenosphere/binder interface.

2.5. Flexural strength

The flexural strength was measured using ASTM C 78-94. These tests were performed on a MTS™ testing system Model 810. The specimen had a 152.4 mm thickness and height and a 508 mm length, which gave a 457.2 mm test span.

The specific flexural strength for all batches can be seen in Fig. 7. B1 showed a flexural strength of 0.16 ± 0.01 MPa/kg. When cenospheres were added in B2, there was no drop in flexural performance. B3 was also unchanged within experimental error at 0.17 ± 0.01 MPa/kg. B4, which has the highest concentration of cenospheres, did show a drop in flexural performance to 0.12 ± 0.01 MPa/kg. The flexural specimens with higher concentrations of cenospheres also showed the coarse aggregate pop out that was seen earlier in the tensile specimen.

2.6. Fracture toughness

There exists no standard test method for the determination of fracture toughness in concrete. ASTM 5045, a

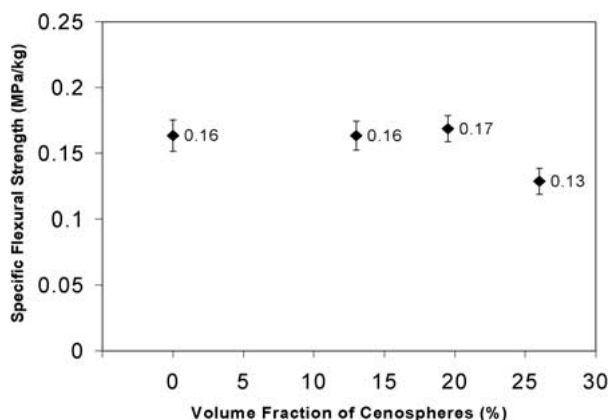


Figure 7 Specific flexural strength of concretes with varying volume fractions of cenospheres.

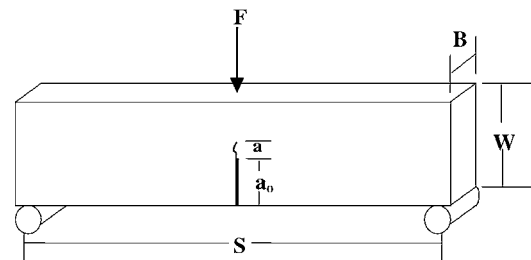


Figure 8 Fracture specimen geometry.

standard method for composite fracture toughness was employed instead. The following equation is used to relate load at failure to the critical stress intensity factor, K_{Ic} .

$$K_{Ic} = \frac{FS}{BW^{3/2}} \cdot \frac{3\sqrt{x}(1.99 - x(1-x))[2.15 - 3.93x + 2.7x^2]}{2(1+2x)(1-x)^{3/2}} \quad (1)$$

where F is the load at failure, S is the span, B is the thickness, W is the specimen height, a_0 is the initial crack length and x is $(a + a_0)/W$, where a is a correction made necessary by stable crack growth ahead of the initial crack length. The crack geometry can be seen in Fig. 8. This correction is dependent on the compressive strength of the concrete [9]. This increase was calculated using the procedure given by John and Shah [9] and Shah *et al.* [10].

This specimen had a length of 660.4 mm, which gave a span, S , of 609.6 mm. The specimen height, W , was 152.4 mm and the thickness B was 81.3 mm. The initial crack length was around 76 mm but was calculated exactly for each experiment. The specimen geometry can be seen in Fig. 8. These tests were also performed on the MTS™ Model 810.

Fig. 9 shows the specific fracture toughness for all batches. B1 showed a fracture toughness of 0.124 ± 0.002 MPa(m)^{1/2}/kg. There is a drop of 65% in the specific fracture toughness when cenospheres

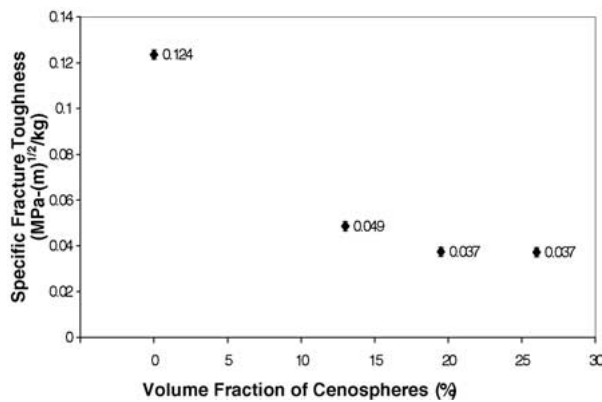


Figure 9 Fracture toughness of concretes using various volume fractions of cenospheres.

are added in B2 to 0.049 ± 0.002 MPa(m)^{1/2}/kg. B3 had a specific fracture toughness of 0.037 ± 0.003 MPa(m)^{1/2}/kg and B4 showed no change at 0.037 ± 0.002 MPa(m)^{1/2}/kg.

Although all concretes tested close to or above industry benchmarks for certain applications, it would be beneficial to improve the overall strength as much as possible. The loss of strength seems to be due to the poor interface properties between the cenospheres and the cement. This can be seen clearly in the SEM micrograph Fig. 10, which shows a cenosphere popped out of the cement matrix. Improving the interface properties of the cenospheres and cement is believed to be the key to performance increase.

3. Surface customization and interface strength

3.1. Surface customization

Three different surface customizations were attempted in order to improve the interfacial strength. These procedures are outlined below.

3.1.1. Silane™ (type A174) treatment

The cenospheres were coated with Silane™ before being mixed into the concrete. This was done in the following manner. A solution of 1080 cc of methanol, 120 cc of water and 4.3 g of Silane™ were mixed and

poured into 428 g of agitated cenospheres. These were allowed to air dry for one day and then oven dried at 50°C for four hours. This recipe would be repeated until enough cenospheres were available.

3.1.2. Silica fume admixture

Concrete batches were mixed similar to the previous batches, but 12% of the cement was replaced with silica fume by weight. The water was also increased slightly to adjust for the higher volume of cement and silica fume. A w/c ratio of 0.45 was normal for these types of concrete.

3.1.3. Combination

It was decided to investigate the idea of a cumulative effect between these two interface modifiers. The concrete was exactly as the silica fume variant but using the Silane™ treated cenospheres.

3.2. Interfacial strength

The interfacial strength of cenospheres and cement was tested using bimaterial fracture mechanics techniques. Once this interfacial fracture toughness was determined, similar bimaterial experiments were performed to obtain the fracture toughness of the surface customized system.

3.2.1. Background

A bimaterial system is defined as two dissimilar; linearly elastic materials bonded or cast together. Fig. 11 shows a bimaterial system with a central crack geometry. Material 1 is the more compliant of the two materials.

The bimaterial fracture experiments were done using a central crack geometry loaded in tension. The stress/strain field characterization is performed using what is known as the complex stress intensity factor [7].

$$K = K_1 + iK_2 \quad (2)$$

This factor completely characterizes the stresses around the crack tip and shows a coupling of the opening mode and in-plane shear mode.

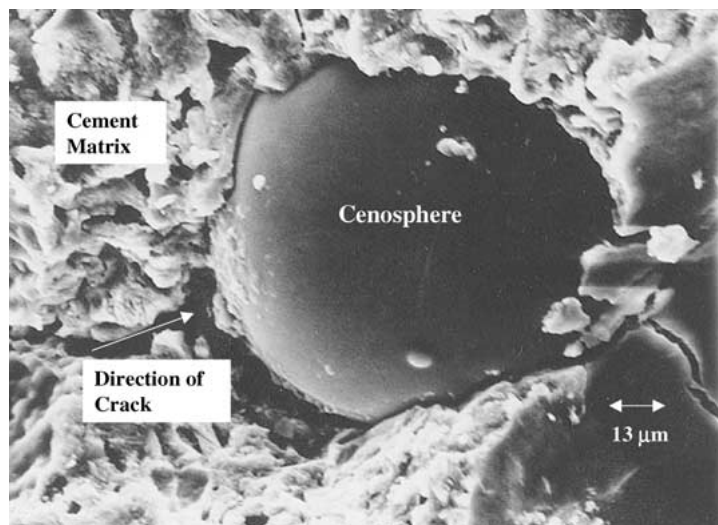


Figure 10 SEM micrograph of a cenosphere in the path of a crack.

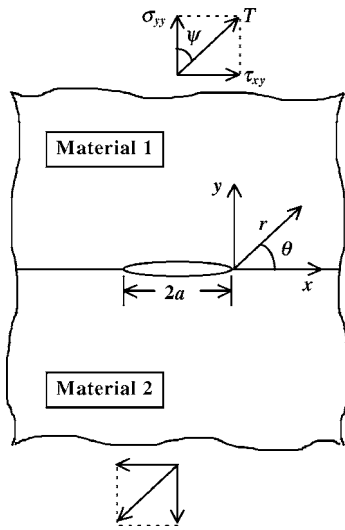


Figure 11 Geometry of a bimaterial fracture specimen.

The material properties are accounted for with the mismatch parameter [7]:

$$\varepsilon = \frac{1}{2\pi} \ln \left(\frac{\frac{x_1}{\mu_1} + \frac{1}{\mu_2}}{\frac{x_2}{\mu_2} + \frac{1}{\mu_1}} \right) \quad (3)$$

where μ_i are the shear moduli and;

$$x_i = (3 - \nu_i)/(1 + \nu_i) \quad (4)$$

where ν_i are the Poisson ratios.

Finally, for a uniaxially stress state ($T = \sigma_{yy}^\infty$) in a central crack geometry, K_1 and K_2 can be expressed in terms of the remote loading [8]:

$$K_1 = \sigma_{yy}^\infty \sqrt{\pi a} [2\varepsilon \cos(\varepsilon \ln(2a)) + 2\varepsilon \sin(\varepsilon \ln(2a))] \quad (5)$$

$$K_2 = \sigma_{yy}^\infty \sqrt{\pi a} [2\varepsilon \cos(\varepsilon \ln(2a)) - \sin(\varepsilon \ln(2a))] \quad (6)$$

where $2a$ is the crack length.

3.2.2. Specimen preparation and test set up

This section discusses the fabrication of bimaterial specimens in which one material was a solid block comprising of aluminum silicate and the other was cast from cement paste without cenospheres. The aluminum silicate represents the cenosphere material while the cement paste represents the binder in a concrete system.

In order to cast the cement paste onto the aluminum silicate block, it was necessary to construct a proper mold. The aluminum silicate block used was 257 mm wide, 257 mm high and 20.07 mm wide. This material was obtained from the Maryland Lava Company and is 99.7% pure aluminum silicate.

The mold was simply four pieces of polycarbonate that would perfectly match the width and thickness and height of the bimaterial specimen. These pieces were

cut out and machined to acceptable tolerances with the addition of three holes evenly spaced from the center in order to form boltholes in the cement casting.

The aluminum silicate block had three holes drilled through, evenly spaced from the center, exactly as was done for the cement, in order to put the gripping bolts in place. The surface on which the cement was to be cast was then sanded with fine grit sandpaper to achieve a very smooth surface. This surface was then cleaned with methanol.

Teflon tape was applied to the exact center of the aluminum silicate block at a thickness of 38.1 mm to represent a central crack. Packaging tape was applied along the edge, which would be removed after casting to make a pure interface. Then silicon was applied around the block to reduce water leakage.

The polycarbonate pieces were then arranged around the block to form the mold. These were all clamped firmly in place and then all joints were sealed with silicon to prevent leakage. The silicon was allowed to dry for one hour.

The cement paste was prepared a water/cement ratio of 0.4 with all needed admixtures. This paste was poured into the mold from the top in three evenly spaced lifts. After each lift was placed into the mold banging the mold rigorously consolidated it. This also achieved the goal of removing all air from the paste.

After the final lift was introduced and initially consolidated, three 9.525 mm bolts were placed into the holes. This required that the cement in the mold be consolidated further to ensure that the cement is uniform around the bolts. These bolts are to be removed after a few hours when the cement is firm but not completely hardened. If the bolts are removed after a complete cure, they can cause considerable cracking.

The top of the mold is then sealed to reduce water evaporation and the entire structure is allowed to cure for 48 hours. The polycarbonate pieces are then carefully removed leaving the completed specimen seen in Fig. 12 and loaded into the testing apparatus. These specimens were then loaded in tension until failure.

3.3. Results and discussion

Following the experiment, the maximum load at failure was converted to stress and applied to Equations 5 and 6 to determine the values of the critical complex stress intensity factor. After conducting five experiments an average value of $K_{2c} = 0.068 \pm 0.001 \text{ MPa(m)}^{1/2}$ and $K_{1c} = 0.002 \pm 0.001 \text{ MPa(m)}^{1/2}$ was found.

This is an extremely low value for a bimaterial interface. As a comparison, the bimaterial fracture toughness of an aluminum-polycarbonate interface is $K_{1c} = 1.00 \text{ MPa(m)}^{1/2}$ and $K_{2c} = 0.5 \text{ MPa(m)}^{1/2}$.

This quantitatively shows where the weakness in this material lies. To improve the strength of this material, one must improve the properties at the cement/cenosphere interface. The results of attempts to improve the interfacial properties are outlined in the following paragraphs.

The silica fume showed impressive results. After conducting five experiments, an average $K_{1c} = 0.167 \pm 0.001 \text{ MPa(m)}^{1/2}$ and $K_{2c} = 0.004 \pm 0.001 \text{ MPa(m)}^{1/2}$

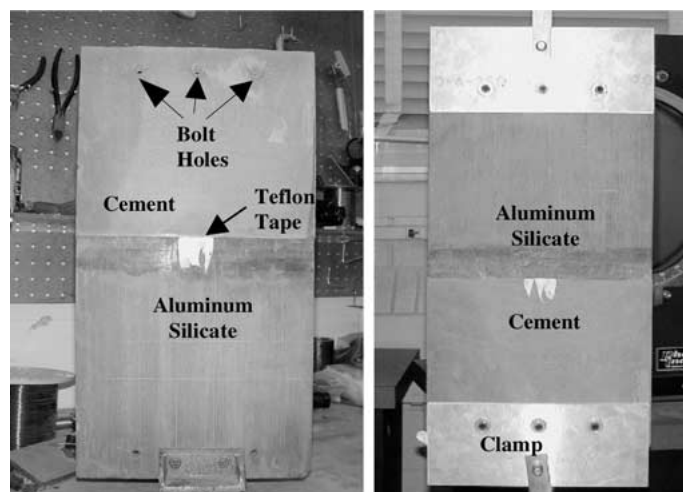


Figure 12 Bimaterial specimen after removal from mold (left) and the bimaterial experimental setup (right).

was found. This represents a 146% improvement in the interfacial fracture toughness.

The Silane™ was even more impressive showing an average $K_{Ic} = 0.193 \pm 0.002 \text{ MPa(m)}^{1/2}$ and $K_{2c} = 0.006 \pm 0.001 \text{ MPa(m)}^{1/2}$. This represents a 184% improvement.

These tests have shown that the ability to improve the interfacial bond of cement and cenospheres can best be achieved using the surface treatment Silane™ and the admixture silica fume.

It is easy to understand why the silica fume works so well. Silica fume is 100 times smaller than cement, which gives it a microfiller effect. The silica fume particles are easily introduced between the cement grains. This effect reduces the space available for water and acts as a nucleation site for hydration products. There is also a pozzolanic effect. The particles are amorphous silica (+85% SiO₂) with an extremely high surface area. This reacts chemically with calcium hydroxide found in cement and forms calcium silicate hydrates or CSH. Increased CSH leads to higher strength.

It is not so easy to understand why Silane™ works. It is possible that Silane™ decreases surface wetting decreasing the formation of calcium hydroxide, which weakens the interface.

These materials needed to be tested under real working conditions. It was decided to do small batch compression tests before committing to large-scale batches.

3.4. Small batch compression tests

All specimens were 50% cenosphere and 50% cement by volume, except when silica fume was added, and prepared according to ASTM C192-95. The results of these experiments can be seen in Fig. 13. As was the case with previous observations, the addition of cenospheres decreased the compressive strength when compared to the control concrete from 21.14 MPa to 13.96 MPa. About 45% of this strength is regained with the addition of the Silane™ cenospheres. Even more encouraging is that more than 100% of the initial strength is regained with the addition of silica fume with an average compressive strength of 21.59 MPa. Although the combination of these two interface modifiers did not show cumu-

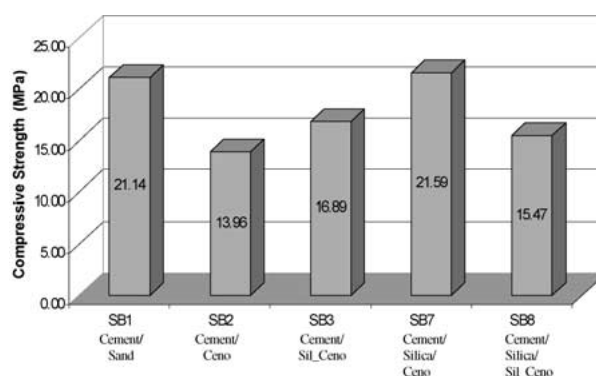


Figure 13 Results of small batch compression tests of various interface modifiers.

lative results with an average strength of 15.47 MPa, which is lower than Silane™ alone.

These tests showed that although Silane™ shows promise as an interface modifier, more study would be needed to properly apply the procedure to real world situations. This along with a higher unit cost and difficulty in making large batches, it was determined not to attempt a large batch of Silane™ cenosphere concrete at this time.

On the other hand, the results of the silica fume in both the interface experiments and the small batch experiments along with the low cost and ease of mixing led to the decision to pursue the making of a large batch of silica fume/cenosphere concrete and compare the results to previous concrete with the same amount of cenospheres.

4. Properties of improved concrete

The mix design of the final batch was similar to concrete B4, although 12% of the cement by weight was replaced with silica fume. This translated to 262 kg of cement and 36 kg of silica fume. It was also necessary to increase the water content slightly to allow for the higher volume of cementing materials. This batch was designated B1SF and was mixed and cured for twenty-eight days according to ASTM C192-95. This concrete was then compared to B4, which was similar to B1SF in all respects except for the addition of silica fume. This side-by-side comparison can be seen in Table II.

TABLE II Comparison of cenosphere concrete with and without silica fume

Property	Cenospheres alone (B4)	Cenospheres w/silica fume (B1SF)	% Change
Density	1810 ± 34 kg/m ³	1840 ± 30 kg/m ³	+2%
Specific compressive strength	6.69 ± 0.32 MPa/kg	12.05 ± 0.36 MPa/kg	+80%
Specific tensile strength	0.72 ± 0.03 MPa/kg	0.97 ± 0.04 MPa/kg	+35%
Specific flexural strength	0.12 ± 0.01 MPa/kg	0.20 ± 0.01 MPa/kg	+40%
Specific fracture toughness	0.037 ± 0.002 MPa(m) ^{1/2} /kg	0.052 ± 0.001 MPa(m) ^{1/2} /kg	+41%

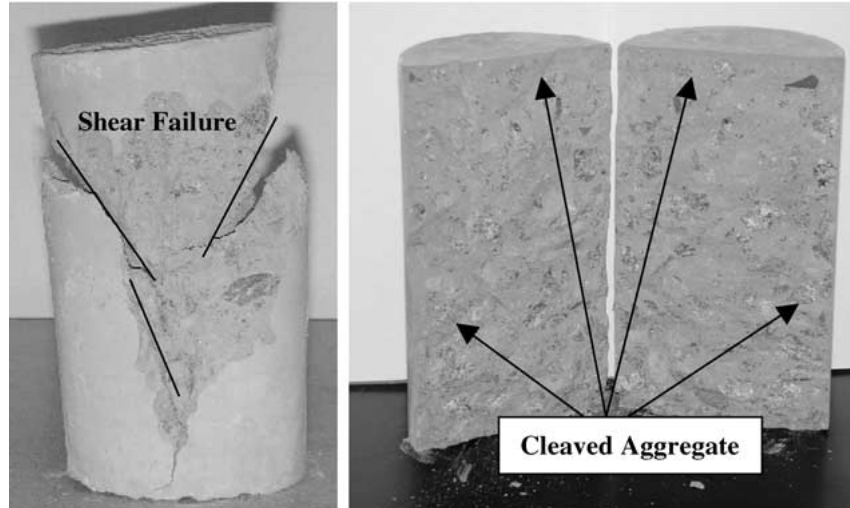


Figure 14 Failure modes of cenosphere concrete after the addition of silica fume. On the right, a compressive specimen showing shear failure, and a tensile specimen showing cleaved aggregate and no “pop out”.

- A density of 1840 ± 48 kg/m³ was very similar to the density of B4, which was 1810 ± 34 kg/m³. The slightly higher density could be due to the increased water content.
- The compressive tests showed that B1SF had a compressive strength of 12.05 ± 0.36 MPa/kg. This is an 80% improvement over B4.
- The tensile tests showed B1SF to have a tensile strength of 0.97 ± 0.04 MPa/kg. This represents a 35% improvement over B4.
- The flexural strength of B1SF was determined to be 0.20 ± 0.02 MPa/kg. This represents a 40% improvement over B4.
- The fracture toughness of B1SF was determined to be 0.052 ± 0.001 MPa(m)^{1/2}/kg. This was a 41% improvement over B4.

It was also interesting to note that not only were the properties of the cenosphere concrete improved by the addition of silica fume, but the modes of failure showed that improved interfacial properties were the key to these improvements as previously suggested. Fig. 14 shows a compressive and tensile specimen after failure. The compressive specimen shows mostly shear failure and the tensile specimen shows very little pop out of the coarse aggregate. This reduction in aggregate pop out was also seen in both the flexural and fracture specimens after failure.

5. Conclusion

A study has been conducted in which a new lightweight concrete using ceramic microspheres, called cenospheres, was investigated.

The viability of this type of concrete was determined, after which all the mechanical properties were characterized using various volume fractions of cenospheres. The properties of the concrete were then improved using interfacial modifiers.

After the first part of this study, in which this type of lightweight concrete was deemed viable, the mechanical properties were determined with different levels of success. The concrete exhibited acceptable levels of strength in all tests for all volume fractions of cenospheres. However, there was a trend of decreasing strength with higher volume fractions of cenospheres. This loss of strength was determined to be due to the poor interfacial strength properties between the cenospheres and the binder material. It was decided that in order to improve the concrete’s performance, this interfacial strength needed to be improved.

The interfacial strength was quantified using bimaterial fracture toughness techniques. This allowed the interfacial fracture toughness between the cenosphere and the cement to be quantified, after which interfacial modifiers could be tested. These tests led to two possible candidates. The coupling agent Silane™ and the admixture silica fume. Due to ease of manufacture, cost restrictions and performance, the admixture silica fume was chosen as the prime interface modifier.

The addition of silica fume to a concrete with a high volume fraction of cenospheres yielded impressive results. Although the lowered density remained virtually unchanged, there was an 80% improvement in compressive strength, 35% improvement in tensile strength, a 40% improvement in flexural strength and an 41% improvement in fracture toughness.

The manufacture of a high-performance lightweight concrete using cenospheres is possible. Furthermore, the availability of the materials used in the development of this concrete is readily available and relatively cost effective. There are no special processes necessary and the concrete can be mixed at any existing concrete producing facility.

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