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FOAM GLASS LIGHTWEIGHT AGGREGATE: THE NEW APPROACH

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ABSTRACT

Foam glass lightweight aggregate (LWA) derived from mixed waste and recycled glass has great potential for use as an alternative material for several applications in building and other industrial applications. Despite the significant superior features of the current product, there is still room for further research to improve the structural performance of newly developed foam glass and foam glass-ceramics produced from waste and recycled materials. Improvements may be achieved through controlling microstructures and the distributions of pore sizes and shapes, altering chemical and phase compositions, creating reinforced structures by the inclusion of other fibrous materials as well as adding colour to the foam glass and glass-ceramics. One commercially used foam glass gravel has been selected and was the subject of a wide range of tests to determine its physical and mechanical properties and to compare them to conventional products in the industry. Results obtained from percent crushed particle content, abrasion resistance and freezing and thawing resistance testing are presented and analysed. Methods for improving foam properties and expanding its usefulness in engineering applications are proposed; adjusting the microstructure characteristics and changing the chemical and phase composition were found to be effective. A deeper examination of the microstructure by microscopy (SEM or TEM) further revealed the promising features of the evaluated material as a new versatile construction material. In addition, inclusion of colouring oxides in foam formulation was examined as an innovative way for increasing mechanical strength in a colourful product.

Keywords: Foam glass-Lightweight aggregate-Colour foam glass-Ceramic frits

1. INTRODUCTION

Foam glass is generally composed of 98% recycled glass. It is considered one of the best solid isolation materials with a number of unique properties. The material comes in various shapes and sizes (aggregates, blocks and granules) and has found many different application areas in building and construction industries. Horpibulusk et al. (2014) discusses how lightweight fill materials are increasingly being used in civil engineering applications such as backfills, slope stability, embankment fills, pavement and pipe bedding. Arulrajah et al. (2015) discusses how the applications of lightweight fill materials are fairly broad but the main intent of this material is to significantly reduce the weight of fills, thereby mitigating excessive settlements and bearing failures. Due to their porous structures, they are lightweight and have distinctive properties such as fire retardant and noise insulating characteristics. Janetti et al. (2015) discusses that foam glass is best used as thermal insulation of building foundation and cellar plates, as backfilling of voids or overflows in structural engineering or as cost-effective insulation for long-scale thermal energy stores.

In the past, the shortage of recycled glass linked with a high production cost confined foam glass usage to specific applications such as underground piping jackets or tank and vessel insulation covers. However, recent advances in manufacturing technology and the abundance of used glass supplies have made it possible for foam glass to become a more economically viable commodity. Increased health-consciousness amongst the general public as well as the need to eliminate the devastating environmental hazards caused by organic and polymeric wastes have prompted the increased use of glass containers in food and beverage industries. Moreover, rapid technological advancements in electronics industry have generated even more glass wastes due to a large number of discarded computer and TV monitors. As a result, there has been an increase in research on how to use contaminated recycled glasses for the production of foam glass. Mugoni et al. (2015) has investigated the use of recycled florescent lamps to produce foam glass as an interesting way for waste prevention and waste management, developing new products with commercial potential. Konig et al. (2015) investigates the excellent potential of cathode ray tube (CRT) panel glass foamed with carbon and MnO_2 for the production of foam glass with improved heat-insulating ability.

The use of recycled and waste glass in foam glass production has many environmental benefits. Foam glasses are generally classified as green products, as they contribute to considerably lower CO_2 emissions and less environmental pollution in the process of foam glass production compared to any other industrial process which incorporates recycled glass as a feeding constituent.

Foam glass can be widely used in many applications such as basement walls, foundations, floors and roofs, terrace and garden covers, rooftops and parking areas (Ayadi et al., 2010). Other possible city infrastructure construction usages are in parks and yard areas, pedestrian and bicycle paths, railway embankments, sports fields and many other applications, which introduces substantial savings in cost energy and maintenance. During the past few years, there have been many studies on using recycled glass as aggregates in lightweight concrete (Limbachiya et al., 2011; Shi et al., 2007; Bumanis et al., 2013). Not only does the excellent water permeability of the foam glass aggregates allow proper drainage of water from the road surface seeping through small cracks, but also it reduces susceptibility to freezing and thawing phenomena such as ice lenses. The improved drainage capacity provides for a shallower road preparation depth. Compared to natural aggregates, foam glass requires less depth of road preparation, dirt removal and aggregate replacement.

Current research work focuses on examining the engineering properties of two manufactured foam glass aggregates delivered by Foamyna Canada Inc. and tested at the Centre for Pavement and Transportation Technology (CPATT) of University of Waterloo. Additionally, the engineering properties of the newly developed foam glass aggregate known as LWA will also be assessed and discussed. The chemical and physical properties of the foam glass were improved by controlling the material microstructure characteristics, and novel approaches were investigated to modify the pore sizes and shapes and develop more uniform pores with controlled sizes. The incorporation of colouring agents has created a range of coloured foam glass with ideal properties and increased strength for use in various road construction applications. The features and significant benefits of this new material could still be increased to a very high level compared to similar materials, by creating a new controlled microstructure which may be reinforced by the presence of other fibrous and nano-scale material. The market for porous, lightweight, cost-effective and environmentally friendly material such as foam glass and glass-ceramics, in different colors, shapes and sizes, having innovative and improved chemical, physical and mechanical properties is becoming extremely important. This will make them ideal materials for future use in both buildings and road construction.

2. 2. EXPERIMENTAL PROCEDURES

2.1 Physical Characterization of LWA

CPATT has been supplied with quantities of two distinct foam glass LWA materials, designated as LWA-A and LWA-B. Both materials were produced by melting down recycled glass and mixing it with air and with trace quantities of chemical additives to form a highly porous, rigid foamed glass product with a bulk and absolute density substantially lower than that of water. For the purposes of the physical properties testing, the engineering assessment to date has included Grain Size Analysis, Crushed Particle Content, Flat and Elongated Particle Content, Abrasion Resistance Testing and Freezing and Thawing Resistance Testing.

Visual examination showed that both materials possess a highly vesicular structure. By relative comparison between the two materials, LWA-A appears darker grey in colour, while possessing smaller or finer voids than LWA-B and having the lower apparent density in hand specimens. Material LWA-B appears a uniform light grey in colour, with larger or coarser voids in its matrix and appearing denser in hand specimens than LWA-A. Both materials appear to be quite brittle and prone to damage in handling, necessitating the use of hand sieving for grain size analysis in lieu of mechanical sieving. A visual comparison of LWA-A and LWA-B can be seen below in Figure 1.

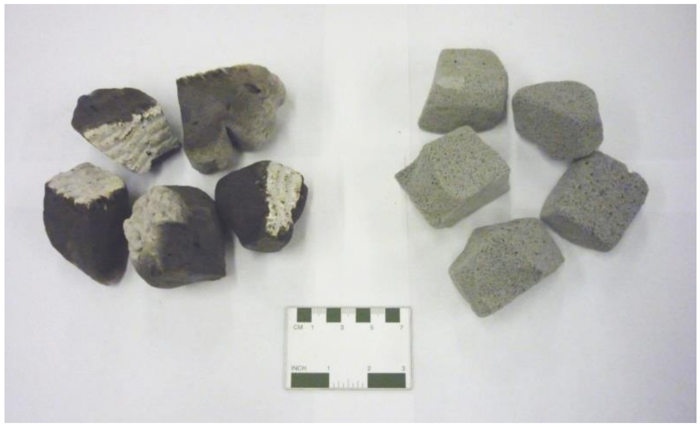

Figure 1: Comparison of visual appearance between LWA-A (left) and LWA-B (right)

Grain size distribution testing and analysis was performed on materials LWA-A and LWA-B based on MTO laboratory standard LS-602, Method of Test for Sieve Analysis of Aggregates. In total, six samples of a minimum of 10 kg each were obtained and analyzed, including three samples each of LWA-A and LWA-B. As both materials are coarse aggregates, no sieving was performed on material passing the 4.75mm sieve. LWA-A and LWA-B were both found to have broadly similar grain size distributions. In both cases, all of the material passed the 75mm sieve, with the 63mm sieve being the largest size upon which any material was retained. For both materials, across all samples, less than 10% of the aggregate by mass passed through the 19.0mm sieve. LWA-A had more material on average passing the 4.75mm sieve at an average of 3.7% by mass, while LWA-B averaged 2.6% passing the 4.75mm sieve. Both materials can thus be summarized as relatively coarse aggregates. Figures 2 and 3 illustrate the grain size distribution for material LWA-A and LWA-B.

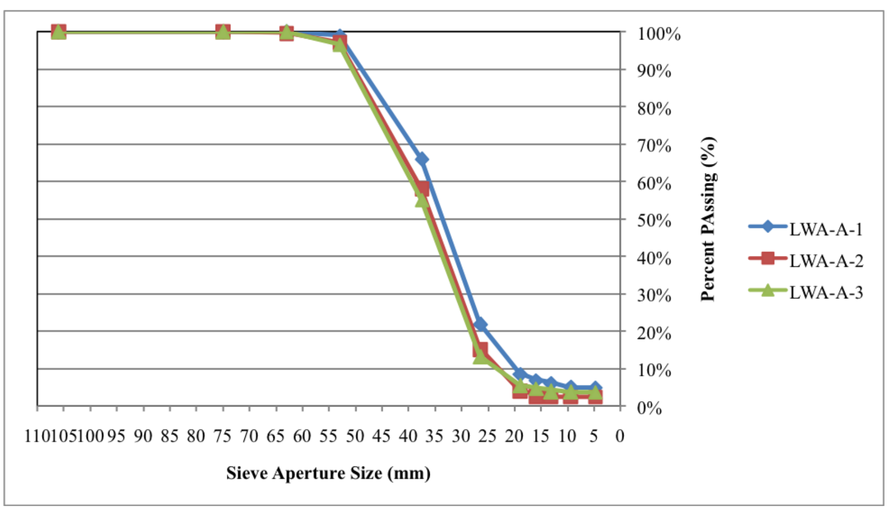

Figure 2: Grain size distribution for material LWA-A

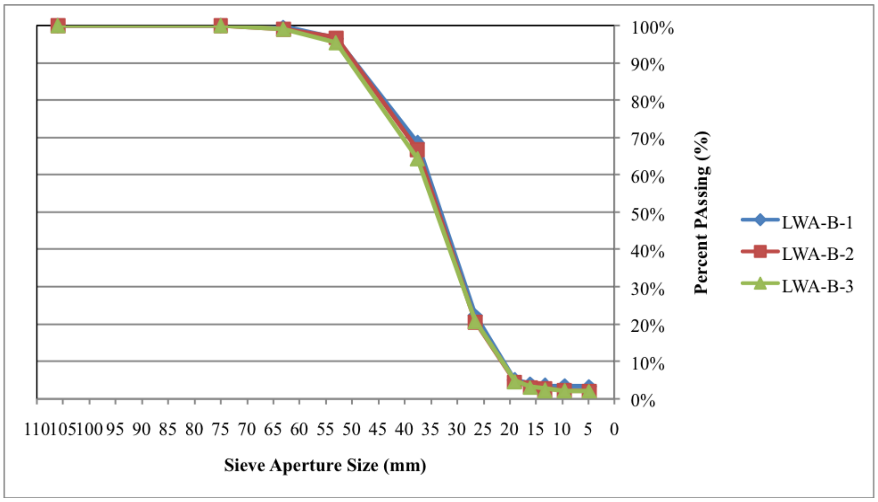

Figure 3: Grain size distribution for material LWA-B

Percent crushed particle testing and analysis was performed on three samples each of materials LWA-A and LWA-B in accordance with MTO laboratory standard LS-607, Method of Test for Determination of Percent Crushed Particles in Processed Coarse Aggregate. The percent content of crushed particles was determined solely by examining material from the fraction passing the 26.5mm sieve and retained upon the 19.0mm sieve. For material LWA-A, the three samples were found to have crushed particle contents of 99.4%, 99.3% and 99.7% on a mass basis, for an overall average of 99.5% crushed particles. For material LWA-B, all three samples taken consisted of 100% crushed particles. For both materials, this compares favourably to Ontario Provincial Standard Specification (OPSS) 1010, which governs requirements for granular fill materials in use in pavements in Ontario. OPSS 1010 prescribes a minimum of 50% crushed particles by mass for Granular S class materials, 60% crushed particles for Granular A and Granular M, and 100% crushed particles for Granular B Type II and Granular O.

Percent flat and elongated particle content testing and analysis was performed on three samples each of materials LWA-A and LWA-B in accordance with MTO laboratory standard LS-608, Method of Test for Determination of Percent Flat and Elongated Particles in Coarse Aggregate. One modification was made to the LS-608 procedure. The mass amount examined for each test was reduced from 3000g to 1500g for the fraction passing the 37.5mm sieve and retained upon the 26.5mm sieve, and from 2000g to 1000g for the fraction passing the 26.5mm sieve and retained upon the 19.0mm sieve. This change was followed as the original specified mass amounts would have corresponded to a much greater volume of particles of the lightweight aggregates than would be the case for a natural aggregate. For material LWA-A, the three samples were each found to have flat and elongated particle contents of 0.2% by mass, for an overall average of 0.2%. For material LWA-B, the three samples were found to have flat and elongated particle contents of 0.1%, 0.1% and less than 0.1% by mass for an overall average of 0.1%.

Abrasion resistance testing was conducted on the two materials using a Micro-Deval apparatus. The Micro-Deval testing was based on MTO laboratory standard LS-618, Method of Test for the Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus, with a number of modifications to compensate for the low density of the LWA materials. Grading A was selected from LS-618 as both LWA materials are coarse aggregates with a nominal maximum size which is much greater than 16.0 mm (for Grading B) or 13.2 mm (for Grading C). For LWA-A, percent losses during Micro-Deval tests were 4.6%, 3.7% and 9.2% for an overall average percent loss of 5.9%. For LWA-B, percent losses were 1.8%, 3.2% and 4.4% for an overall average percent loss of 3.1%. This is within tolerances established by OPSS 1010, which specifies maximum coarse aggregate abrasion percentage losses by mass of 21% for Granular O, 25% for Granular A, Granular M and Granular S, and 30% for Granular B (Types I, II and III) and for Select Subgrade Material (SSM).

Freezing and thawing resistance testing was conducted on materials LWA-A and LWA-B based on MTO laboratory standard LS-614, Method of Test for Freezing and Thawing of Coarse Aggregate. The freeze-thaw test was conducted on particles from both LWA materials in the size fractions ranging from 37.5mm to 26.5mm and from 26.5mm to 19.0mm. As the LS-614 specification does not cover lightweight aggregates, European Standard BS EN 13055-2

Annex B specifies a procedure for testing of freezing and thawing resistance of lightweight aggregates, whereby a sample volume of 1500mL is required for freeze-thaw cyclic testing on materials which have a maximum aggregate size of 16mm to 32mm. For material LWA-A, percentage losses for each sample were found to be 0.5%, 0.2% and 0.1% by mass, for an overall average of 0.3%. For material LWA-B, percentage losses for each sample were found to be 0.01%, 0.1% and 1.4% by mass, for an overall average of 0.5%. Again, this compares favourably to the OPSS 1010 standard, which specifies a maximum unconfined freeze-thaw percentage loss of 15% for Granular O, with no limits stated for other classes of granular materials.

2.2 Material Formulation and Test Samples

The materials considered for the preparation of coloured and non-coloured foam gravel LWA are listed below. It should be noted that apart from the additives, the main materials have molecular structures similar to glass which develops a more uniform cellular pattern in the final product.

- Mixed recycle container glass;
- Waste flat glass;
- Dumped CRTs from TVs and computer monitors;
- Frits and glazes (transparent and opaque);
- Foaming agents such as silicon carbide (SiC);
- Steel industry slag;
- Colour oxides and ceramic pigments;
- Other additives such as clays

Using different combinations of the above materials, foam glass samples are produced and assessed for their final quality in accordance with the area of intended applications.

The first step in the sample preparation process is to pulverize all the ingredients in the formula prior to weighing and mixing. The mixture is prepared in accordance to a given recipe. It is then ground in ball mills to reach D90<200 mesh in particle size. It is sieved and milled repeatedly so that all particles are under 75 microns (µm). The binding agent is added and the mixture is formed using an appropriate forming apparatus. Finally the foams are fired under a specific thermal cycle to achieve the required stability and uniformity.

2.2.1 Methods

Two methods of both direct and indirect types were employed. In the direct method, ingredients are used without being processed prior to mixing stage, whereas in the indirect method, waste materials of a non-glassy nature are selected and processed to acquire a glassy structure before being used in the formulation. The latter technique allows for the creation of additional favourable characteristics. Choosing the proper method depends on the type of wastes used in the foam formulation.

2.2.2 Results

Wastes from ceramic frit manufacturing plants can universally be used as the basic element in making foam glass. Any kind of melted frit with an amorphous structure will be useful in this process. The main advantage of frits over other materials for use as the base element in foam production is its basic molecular structure which provides more suitable physical and chemical properties. As in any other industrial product, chemical and physical characteristics of different frits can vary. It is therefore recommended to consider these properties and modify the frit in accordance with the final foam requirements. In addition, foam characteristics can be conveniently controlled by changing frit percentage in the formulation. Important parameters including density, mechanical strength, thermal conductance, flammability, coefficient of thermal expansion and chemical strength can be adjusted for any application requirement. This makes waste frits an ideal ingredient in the formulation recipe.

The microstructure variations in foams can be studied by Scanning Electron Microscopy (SEM). Figures 4, 5, 6 and 7 demonstrate the capabilities of SEM in evaluating and thus controlling the end results. Figures 4 and 5 show a scanning electron microscope image of the homogeneous microstructure of foam glass with approximate uniform cellular shape and sizes obtained by using waste of ceramic frits and glazes under a firing condition of 800°C and 30 minutes of firing cycle. Figures 6 and 7 are SEM images of the damaged microstructure of foam glass obtained by using waste of ceramic frits and glazes produced under a firing condition of 900°C and 30 minutes of firing cycle. As shown, the increase in the firing temperature from 800°C to 900°C destroys the cellular structure of the foam glass.

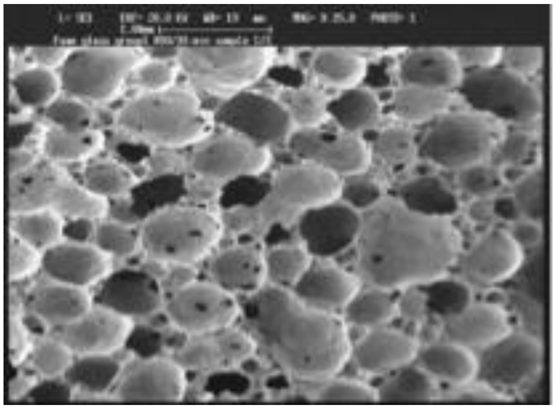

Figure 4:Homogeneous microstructure of foam glass

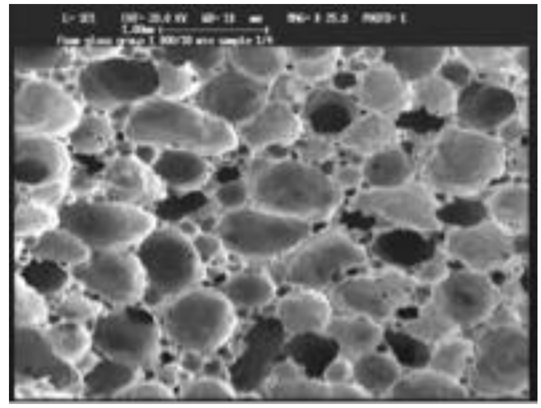

Figure 5:Homogeneous microstructure of foam glass

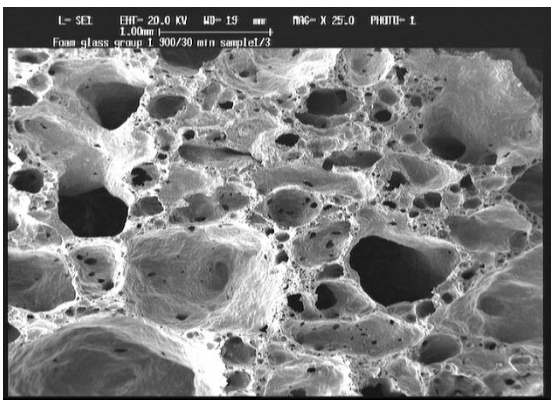

Figure 6: Damaged microstructure of foam glass

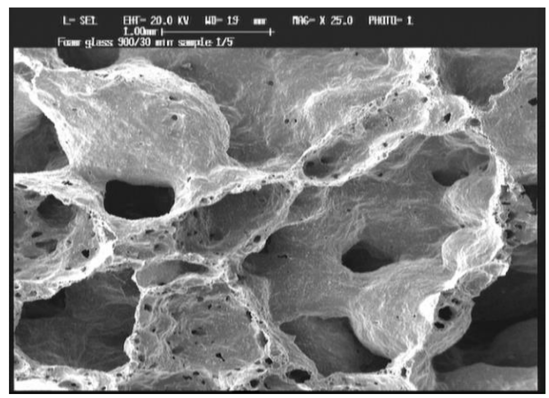

Figure 7: Damaged microstructure foam glass

Foaming agents are another important parameter in the course of foam development. It is found that pure silicon carbide possesses superior foaming capacity which makes it one of the most suitable constituents in foam glass production, in particular when ceramic frits and glazes are part of the components in the formula. Experiments were carried out to determine the foaming capabilities and the end product features at different SiC weight values and in a temperature range of 800-900°C, undergoing a 30 minute heating cycle. Figures 8 and 9 show the foam structure produced in a sample containing 19.6% waste transparent frit compared to the standard foam glass using 2% SiC with the firing temperature at 800°C. Figure 10 is an image of foam glass made from ceramic frits and glazes with varying SiC contents. Foam configurations in different samples produced by using ceramic waste frits and with increasing SiC content show that as temperature increase to 850°C, a uniform foam structure is developed (Figure 10). Raising the temperature over 850°C has caused deformation in the microstructures of foams.

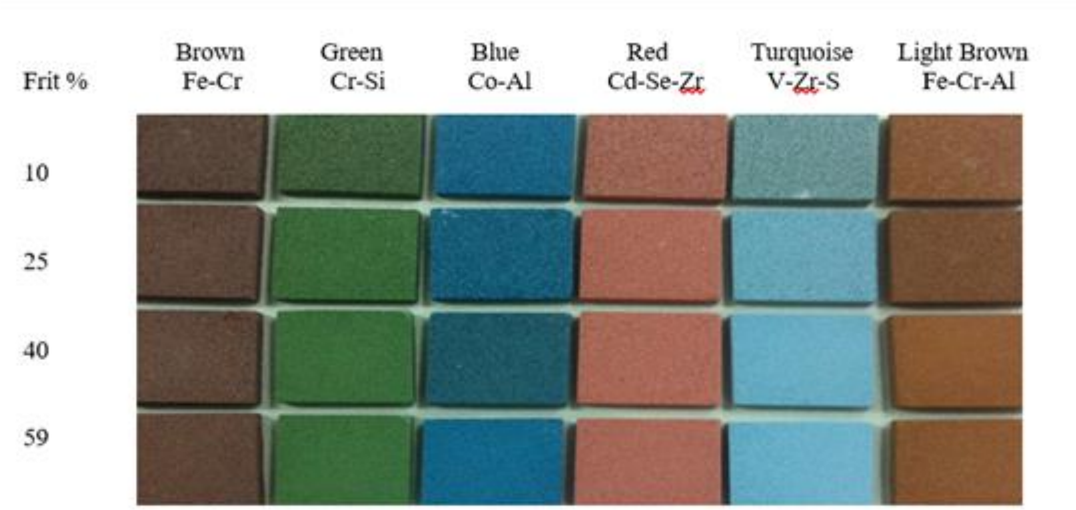

Figure 11: Direct method producing coloured foam glass by adding different percentages of waste ceramic frits and glazes to mix glass to improve colour quality

Another promising feature in the present work is development of coloured foams which are expected to find a bright future in road and highway signs and traffic codes. The physical inclusion of ceramic pigments in the glaze composition yields shades with excellent quality. Therefore it can be concluded that presence of ceramic frits or glazes in the foam composition helps to enhance its colour quality. It should be noted that transparent frits increase the colour density and produce darker shades whereas the so called opaque frits have tendency to produce light pastel colours. Figure 11 demonstrates various coloured foams produced by direct pigment inclusion. Coloured foams such as LWA can have excellent applications in road industry.

Raising the temperature over 850°C causes the deformation in microstructure. Foaming agents are formulated in such a way as to obtain maximum performance with minimum quantity. Pure silicon carbide is the main bubbling agent in this test and is used as foaming component with darker products. Other agents are employed to give soft colour and clear effects.

3. DISCUSSION AND CONCLUSION

Initially, physical properties testing was carried out at CPATT on the two lightweight aggregate materials, designated as LWA-A and LWA-B. The tests included grain size analysis, crushed particle content, flat and elongated particle content test, abrasion and freeze-and-thaw testing. The laboratory tests indicated that both samples have a very consistent and repeatable gradation with high percentage of coarse aggregate. They both have very high crushed particle contents and very low flat and elongated particle contents. Overall, the LWA materials showed excellent physical and mechanical characteristics and conform to most of the OPSS 1010 requirements for granules A, M, O or S. Both materials are concluded as suitable for use in pavement structures.

Based on the promising initial results, more intensive research work has continued to establish techniques for monitoring foam capabilities at the microstructure level. It has been concluded that the physical and mechanical properties of the foam glass can be controlled and altered according to specific needs at the very early stages of composition preparation. Important mechanisms are introduced which conveniently enhance flexibility in changing and modifying foam characteristics. The addition of small percentage of ceramic frit to the base formulation can have significant influence on important qualities such as cellular structure, surface water absorption, viscosity and density. Other physicochemical specifications can be modified and tailored as required by adjusting the frit content in the mixture of raw materials, while the use of SiC as a foaming agent has been determined to be a second versatile controlling mechanism. Volumetric expansion, density and colour stability in foams can be altered by varying quantities of SiC in mixture contents. Finally, ceramic stains are confirmed as ideal substances for producing colourful foam glasses. Impressive coloured foams, considered as multifunctional elements, can find considerable demand in road and highway construction operations.

The fundamental research work has disclosed excellent mechanisms for customizing foam properties according to the sector of application. In continuation of present studies and in order to supply proper samples for the ongoing experimental works at UW, new foam products with modified compositions will be the subject of future research. The capabilities of glass foams as environmentally friendly and green substances will be further explored and developed. A deserving place for many varieties of foam glass is anticipated in the ever-expanding construction industry and its important related markets.

4. ACKNOWLEDGMENTS

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