GLASS RECYCLING IN WASTE MANAGEMENT

BY

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Declaration

I declare that the work in this thesis report entitled GLASS RECYCLING IN WASTE MANAGEMENT has been performed by me in the Department of Industrial Design Ahmadu Bello University Zaria, Nigeria and Institute of Materials Processing Michigan Technological University Houghton, United States under the supervision of Professor C.A Okuofu, Professor A.M Ahuwan and Professor J.Y Hwang. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at any university.

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Certification

This Thesis entitled **Glass Recycling in Waste Management** by Garkida, Adele Dzikwi meets the regulations governing the award of the degree of Doctor of Philosophy in Industrial Design (Glass Technology) of Ahmadu Bello University Zaria. It has this day been approved for its contribution to knowledge and literary presentation.

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Dedication

This work is dedicated to my mom Flora Dzikwi my very first Teacher, to my dad Dzikwi Garkida for believing in my capability and to my role model Adele Gingrich Pogue.

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Abstract

Glass is a recyclable material, and in a country of about 120 million people with increasing urbanization, industrialization and standards of living, it is necessary that resources are continuously sourced and managed for sustainable development. In Nigeria today, the populace are yet to be aware of waste glass recycling let alone making sure that the waste glass they generate should be contaminate free, therefore most glass wastes that would be collected from neibourhoods would be expected to be contaminated and such material even though cannot be used for making containers, they can be directed to lower valued uses, such as road aggregate or glassphalt. There are different processes for the utilization of cullets for manufacture of new glass. These processes include remelting and sintering. cullets can be used as crushed to be remelted in pots or furnaces for use to make new products or sintered which involves the use of powders. This study sought to convert the glass waste of Light tubes and window glass (soda- lime silica glass), drinking glass (lead crystal glass) and laboratory glass (borosilicate glass) to functional forms using the sintering method. The glass samples were analyzed using the ICP technique to determine their chemical composition. Two different grain sizes comprising of 106 micrometre mesh and -75 micrometre were taken from each sample to produce the powder compacts with the hope of achieving better compaction and more full density on fusion. 10g was weighed each time of every sample and pressed using uniaxial press, forming three sets of compacts. The first containing no binder pressed at 5,000 psi and 10,000 psi, the second set contained binder pressed at 5000 psi and the third set contained binder and also pressed at 10,000 psi. 29mm (1.15”) diameter and 10 mm of maximum thickness compacts were made. The samples were fired in an electric kiln at the sintering temperature range of 700 – 750, with holding time of two hours. The drying and firing

shrinkages were measured according to the ASTM C 326, weight, size, warpage, absorption and compressive stress were determined according to ASTM C 67. Additional imperviousness test for glazed ceramic facing tile as specified in specification C126 was also carried out on some of the samples. The microstructures of specimens were observed using a JEOL JSM 820 Scanning Electron Microscope (SEM). Sintering temperature range of 700-750^{o}C was found suitable for composites containing bentonite as binder. The samples sintered at 750^{o}C were very hard and they developed a thin layer of glazing, making it possible to produce a glazed tile all in one process.

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Glossary

Bentonite- Type of clay

Composites- Composition of two or more integrated materials, normally the combination of the materials serves to rectify weaknesses possessed by each constituent when it exist alone.

Cullets – Broken glasses

Densification-it is a process by which a particulate compact is transformed into a ceramic part that has properties to satisfy the needs of specific application.

Drinking glass- Tumblers

Glassphalt – Glass combine with asphalt

Imperviousness – Not allowing liquid to pass through

Light Tubes- Fluorescents tubes

Microstructure – Internal structure of a compact that will help develop the basis for achieving specific properties tailored towards a particular application

Pollution – Destroying the purity of water, land etc

Sintering - Process of forming a dense mass by heating compacted powdered materials.

CHAPTER ONE

INTRODUCTION

Glass is a recyclable material, and in a country of about 120 million people with increasing urbanization, industrialization and standards of living, it is necessary that resources are continuously sourced and managed for sustainable development. Nigeria produces lots of wastes, which if not properly checked and managed will lead to huge economic losses and environmental pollution. Statistics made available by the Nigerian Environmental Society show that 3.04 of the 6.4 million tonnes of wastes generated in Nigeria is accounted for by the city of Lagos alone. Of this 21% is made up of glass, metal, paper, and ash dust (NES 1998 in Ali 2001).

Glass wastes are non-degradable making them even more hazardous when they litter the environment especially to children whose only playgrounds are these refuse areas in a country with poor health care system. They are at a risk of glass related injuries, example tetanus. The need for safe disposal and the search for utility for unwanted glasses cannot be over emphasized, in order to stimulate a reduction of health risks and the conversion of waste to wealth. The possibility of transforming waste to wealth is what is captured by Gonah et al (1997) in a paper presented to the 5th National Annual Conference of NIST, on glass casting using 100% recycled glass in the form of ground glass and Garkida et al (2004) formulated a ceramic glaze containing waste window glass as an alternative to feldspar. Likewise Hwang et al (2006) used mixed coloured post consumer glass as a sintering aid for three types of clay in tiles production. Garkida (2002) believes that using powder technology in stained glass design will contribute to the improvement of the long way in reducing the concentration of lead and mercury in the environment (Garkida et al 2003) as a result of which health hazards will also be reduced. Glass Industries and glass studios for instance will likely pay less for production, if they increase the percentage of their cullets (broken glass) utilization. Garkida et al (2005) confirmed in their laboratory test of recycling waste laboratory glass using the sintering process that these glass wastes can be converted to a raw material for the studio glass making.

The glass industry supports recovery and recycled content requirements that take into account the fact that cullet must meet quality requirements, and that other industries, in addition to the glass container industry, use cullet as an industrial feedstock. It is also critical that an adequate available supply of cullet meets such industrial quality

requirements. Most Nigerian Glass Factories that are already in some form of glass recycling are yet to design waste glass dumps for retrieving waste glass generated in the neighbour-hoods, this if designed properly will improve the quality of waste glass that would be retrieved from the environment.

In Nigeria today, the populace are yet to be aware of waste glass recycling let alone making sure that the waste glass they generate should be contaminate free, therefore most glass wastes that would be collected from neibourhoods would be expected to be contaminated and such material even though cannot be used for making containers, they can be directed to lower valued uses, such as road aggregate or glassphalt.

There are different processes for the utilization of cullets for manufacture of new glass. These processes include remelting and sintering. cullets can be used as crushed to be remelted in pots or furnaces for use to make new products or sintered which involves the use of powders. The characteristics desired in a powder are largely dictated by the properties required of the product (Williams 1963). The demand for impermeability therefore makes severe calls on the control of the sintering process and hence on the nature of the powder itself. All the detailed mechanisms of sintering predict that sintering rates will increase with decreasing particle size, other things being equal (Williams 1963).

1.1 Statement of the Problem

The problem of this study is that glasses lie waste in our streets and at refuse dumps. Most times light bulbs and tubes, bottles and flaconage are just discarded after use. Glass

is a recyclable material and as such this study will attempt to find ways of converting this glass wastes to usable forms. As well as creating glass only dumps that will make easy the collection of glass wastes for recycling, which will result in the removal of glass wastes from the environment.

1.2 Aims and Objectives of the Study

The objectives of this study are as follows

1. To find ways of retrieving glass wastes from the environment
2. To find a way of recycling some of these glass wastes using powder technology.
3. To carry out comparative qualitative tests on the different recycled glass.

1.3 Delimitations of the Study

Glasses that are more generally used would form bulk of the glass waste. This study would be delimited to the most commonly found glass wastes. They are drinking glass (lead crystal glass), fluorescent light tubes (soda- lime silica glass), laboratory glass ware (borosilicate glass) and window glass (soda- lime silica glass).

1.4 Limitations of the Study

Glass powder compaction plays a central role in the evolution of the desired properties in a sintered recycled glass. The densification of the samples would be limited to the type press available for dry pressing. More sensitive equipment for property testing are available outside Nigeria. Access to these equipments is limited to availability of funds. Hence quality of the recycled glasses would be dependent on the available facilities.

1.5 Significance of the Study

The earth has always given and it has always been exploited but only given back very little or left behind destructive wastes. There is the need now to reclaim and rehabilitate the earth. Pollution of the earth occurs by several types of wastes in several ways. And due to the importance of glass in improving the quality of life of man, glass production will continue for a very long time to come. At least 85% of glass making raw materials occurs naturally, which means continuous exploration and exploitation of these materials. And once production is in process, there is bound to be waste, either as a result of unwanted and broken glasses, wrongly formulated batches, gases, heat, and flues, and so on emitted. All these will in turn result in the instability of the environment and economic losses. Unwanted broken glasses in the environment are also hazardous health wise, as they can cause injuries, which may lead to the contracting of tetanus.

This study is therefore significant, as it will seek to;

- Reclaim destructive wastes at the same time rehabilitating the Earth.
- Contribute to good health
- Help the question of sustainability, because any new knowledge acquired would be passed on to others.
- Convert waste to wealth

1.6 Background of the Study

The first glass vessels were formed over 3,500 years ago using the sand core method. These containers were as valuable as gold and were used until broken. Glass blowing

techniques, invented about 1,500 years ago made glass objects more available, but they still remained relatively precious. The Glass Industry with the industrial revolution now produces billions of bottles and billions of tonnes of flat glass each year, resulting in the problem of disposing of or reusing the glass.

There is only one land mass, one atmosphere and a finite supply of water for us to share, to survive let alone maintain dignified life requires that we make the best and least use of these resources. If we do not sustain them they will not sustain us (Royston 1976). Nigeria with a population of over 120 million people will of course produce lots of waste glass resulting to pollution. Pollution acts as an indicator of inefficient processes and if inefficiencies can be reduced then pollution too would be reduced (Royston 1976) while curbing waste generation.

Waste management involves sensing what is there, sorting separating and/or transforming, returning to service what can be used and properly disposing what is left (Rose et al 1972). Recycling glass wastes may be a way of producing usable products at lower cost, providing jobs and minimizing wastes.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Historically waste has always been part of our industrial processes, but mostly viewed as an undesirable byproduct and because of that view, waste management in the past consisted of getting rid of waste in the quickest and cheapest way possible. This often meant taking advantage of free disposal into the air, water and land (Bringer 1992). The natural world is therefore the recipient of human waste materials. Many of these wastes are completely different from natural materials (Bradshaw 1992). The materials flowing into the waste processing system are the products of sophisticated industries; fibre processing, chemicals refining, metal shaping and glass making (Mantell 1975). It would appear that most environmental problems arise because the natural world cannot cope with these novel substances (Bradshaw 1992).

2.2 Waste Generation

In our world today, it is nearly impossible to live a self- sufficient lifestyle, we rely upon technology to support us, a technology which in most cases defies the ability of nature to absorb its impact (Royston 1979), which includes waste generation. These wastes come in many categories that cannot be arranged in order, they range from high volume low cost things example paper all the way to the opposite extreme of low volume high cost example mercury in switches (Rose et al 1972).

Waste generation rates are influenced by climate, cultural habits, economic status, population size and the level of economic development. However personal income has been found to have the most significant effect on waste generation due to its impact on individual consumption pattern (UNDN 1998).

Wastes are inevitable part of human activity. They are either a by- product of initial production process, or they arise when objects or materials are discarded after they have been used (Bradshaw 1992). Waste glass is generated from broken doors, windows, car windscreens, tableware, bottles, flaconnage, fluorescent lamps and light bulbs and so on. The average proportion of waste glass in Nigeria is about 2.8% of solid waste generated. In the mangrove swamp area the proportion is 3.8%. Port Harcourt has 5.9%, Yola 5.7%, Warri 5.2%, Sapele 4.5% and Abuja 4.4%. Those that have lower proportions are Asaba 0.7%, Minna 0.8%, Gombe 1.3% and Makurdi 1.3% (UNDN 1998).

Waste lamps and bulbs are regulated as hazardous wastes because they contain toxic heavy metals. If these lamps are burned or thrown into landfills, the mercury and lead in them can be released into the environment, where contamination problems may occur. Five types of lamps are of concern:

- Fluorescent lamps
- High- and Low-pressure mercury vapor lamps
- Sodium-vapor lamps
- High intensity discharge (HID) lamps
- Incandescent light bulbs

The first four lamps contain mercury in concentrations that exceed the toxicity characteristic leaching procedure's (TCLP) limit. Incandescent light bulbs contain lead at levels that exceed hazardous waste limits. (The TCLP test is a common laboratory test used to determine if solid waste contains harmful concentrations of certain pollutants.) Nearly every business, institution and government agency generates waste lamps and bulbs that could become a hazardous waste problem if not handled properly. (glass environmental policy gpi). Mercury is a very toxic element that tends to accumulate in body tissues. Once it reaches a certain level, it tends to adversely harm the nervous system particularly in children (light bulbs recycling htm 2002), while lead poisoning can interfere with human fertility, resulting in neurological injury leading to death, brain damage, and mental retardation in children (Eisenbud 1978).

2.3 Waste Management

Over the past decade man has begun to consider the importance of his environment and his impact on it. Concerns for the environment are not limited to detrimental effects of pollution but also on the recovery and utilization of resources. Waste reduction can be accomplished by creating less waste initially or by recycling waste products back to the process (Nelson 1992). Steel scrap, non- ferrous metals, glass and small quantities of corrugated paper are the only secondary materials that are reprocessed into products resembling their original application (Henstock 1983). Sand, soda ash and limestone are domestically plentiful. However, using cullet allows the glass container industry to reduce energy input to its furnaces. For every 10 percent of recycled glass used to make glass containers, up to 2-3 percent of the total energy used can be saved. Cullet usage reduces emissions into the atmosphere and when it is added to the batch, the batch is less corrosive to the melting furnace and does not melt at as high a temperature as when only raw materials are used, thus prolonging furnace life. In addition, recycling prolongs the life of waste disposal sites. Waste fluorescent lamps and light bulbs contain toxic heavy metals and are usually hazardous wastes. Businesses, institutions and offices should recycle their waste fluorescent lamps rather than dispose of them in landfills.

2.3.1 *Utilization Rates and Recycled Content*

The glass container industry is committed to increasing both cullet recovery and post-consumer content and approximately 35 percent of all glass containers available to consumers are recycled in America. However, with more state and federal legislation on the horizon, it is critical that the glass industry has flexibility to meet mandated targets.

The industry supports standardized reporting mechanisms. Glass, like plastic, should be able to count cullet tonnage used in secondary glass applications towards recycled content or recovery rates.

Today, the use of commingled collection programs often results in contaminated cullet. Allowing credit for secondary applications also means the glass container industry will not be penalized for recyclers who generate poor quality material. Such material cannot be used for making containers, but can only be directed to lower valued uses, such as road aggregate or glassphalt. The glass container industry endorses equality when it comes to recycling requirements for packaging. Mandating higher recycling requirements for some packages places those containers with higher requirements at a competitive disadvantage. Industries with the higher requirements are forced to spend more resources creating an infrastructure for collecting and remanufacturing their packages.

2.3.2 *Source Reduction*

Most solid waste management hierarchies make source reduction their top priority. Source reduction is generally defined as reducing the quantity or concentration of objectionable components of solid waste before it is generated. Examples of source reduction usually include minimizing, downsizing or lightweighting packaging and eliminating certain objectionable materials as package constituents. Through advances in design and manufacturing technology, the glass container industry continues to reduce the weight of glass containers. For instance, according to a 1992 Franklin and Associates study entitled, Analysis of Trends in Municipal Solid Waste Generation, from the period

of 1972 to 1987, non-returnable glass containers were reduced in weight by about 44 percent.

In addition, source reduction by weight does not address diminishing landfill capacity. After all, landfills fill up by volume, not by weight. Even more importantly, replacing recyclable materials with non-recyclable materials in the name of source reduction is not progress and could have an adverse environmental impact. The glass container, with its easy recyclability and its low volume impact on landfills, is an ideal container in terms of source reduction.

2.3.3 *Solid Waste Management Economics*

Economics is no longer a matter of resources exploitation and production only if we become guardians of the planet can the life of humanity improve (Nisbert 1991). All products eventually reach the end of their commercial life and this necessitates the development of a replacement, which can be based on a new design incorporating latest technology but not necessarily new technology (Wild 1990). Recent causes of wastes are increase in population, urbanization affluence and new materials (Stewart 1967). The natural environment is the sink for the wastes and the source for the resources. Environmental pollution and the depletion of resources are invariably the ancillaries to economic development (Glasson et al 1999). Technology can abate the pollution but at a cost, either of transferring it into another form, which might be more or less acceptable or as a determinable monetary prevention cost (Sinclair in McKnight 1974), thence the solution to technology is more technology (Barta 1992).

The true costs of solid waste management systems are usually unknown. In most cases, landfill tip fees do not cover closure, post-closure, corrective action and replacement costs. As a result, inaccurate comparisons of the cost of recycling with the cost of landfilling are often made to the detriment of recycling.

It is imperative that waste disposal costs be accurately identified. When this occurs, efficiently operated recycling programs will prove to be the least expensive method of solid waste management for the recyclable portion of the waste stream.

2.4 Recycling

Recycling is a manufacturing process. Recyclable materials are basically industrial raw materials. GPI believes that optimal recycling is properly defined as "the remanufacturing or reprocessing of discarded materials into the same product - again and again and again." A proper definition of recycling delineates between primary and secondary recycling. In primary recycling (closed loop recycling), a material is put back into the same product. Making old glass containers into new glass containers, or using old newsprint to create new newspapers is a good example of primary recycling.

The definition of primary recycling was originally adopted by the American Society of Testing Materials in its Thesaurus on Resource Recovery Terminology in 1981. More recently, the U.S. Department of Commerce declared, "to be truly effective in avoiding disposal, a recycling program would have to provide a closed-loop system of reuse or a cycle of continuous reapplication."

Secondary recycling, or cascading, reprocesses discarded materials into other materials or products. Examples of secondary uses for glass include fiberglass, road aggregate and glassphalt. Closed-loop glass recycling is preferred by the glass container industry. However, when this is not economically or technically feasible, secondary recycling is critical to avoid landfilling. (It is important to note that a recovery or utilization rate includes tonnage from both primary and secondary recycling.)

The raw materials for glass making are in abundance world- wide. Silica is inexhaustible, limestone and soda ash are abundant. There is significance to be credited to glass recycling if existing quarries have their lifespan extended and new sites are not developed (Turner 1992). Bottles and jars collected in recycling schemes are sorted manually at recycling depots into clear, amber and green glass. Normally, glass containers are the second largest contributor by weight to a recycling program, exceeded only by newspapers. It is estimated that 90 percent of U.S. communities with curbside recycling programs collect at least one color of container glass. (glass gpi environmental policy).

Containers of different coloured glasses are then taken to a beneficiation plant to improve its quality before reprocessing. At these plants, contaminants such as metals, plastics, ceramics and stones are removed, and the glass is crushed. The cullet is transported to the glass factory where it is used with the other batch materials to make new glass products.

Cullet is technically and economically essential to the glass industry, where its low melting point relative to other raw materials confers distinct advantages by reducing fuel consumption, wear on refractories, cycle time and particulate emission. Cullet utilization

ranges from 8-100%, but it is typically 15- 20% and usually generated within the plant. In green glass most manufacturers accept cullet containing about 25% of other colours. For amber the levels set at about 10%, but for clear glass coloured cullet should not exceed 1% (Henstock 1983).

Glass recycling is a closed-loop system, which means that glass containers can be recycled into new ones over and over again. In some instances, glass may be recycled by its original manufacturer. This material, such as bottles broken in the manufacturing process, never leaves the plant and is easy to reprocess. It is simply ground up and remelted in the appropriate furnace. The manufacturer has to do little sorting or testing because the content of each piece is known in advance. Glass may also be recycled from containers collected from commercial businesses and community sources, most often from curbside efforts, which usually include sorting, either at the collection site or at a processing facility. The following commercial silica glasses have different properties and applications;

- Fused silica glass: Pure silica glass, with excellent chemical durability and very low thermal shock resistance. However, high processing temperatures limit the use of this glass to special applications and it is not commonly recycled.
- Soda lime silica glass: The earliest glass made and the most common. Its application includes plate glass, window sheet glass, container glass, and electric lamp bulb glass. It is relatively easy to melt and fabricate and so it is the target of most recycling operations.

- Lead oxide- alkali silicate glass: These glasses have unique optical and electrical properties that compensate for the added cost of using lead oxide. Its application includes television faceplates, thermometer tubing and some decorated glass objects.
- Borosilicate glass: Heat resistant glasses such as pyrex are commonly of this type.

There are a large number of other glasses used in specialized applications. However these mentioned above are the four, most likely to be encountered in a glass- recycling plant.

Fluorescent light bulbs, U shape light bulbs, and High Intensity Discharge light bulbs (HID) have a certain amount of mercury that will dissipate into the surrounding environment when they break. This is what happens in the case when these bulbs are placed in a landfill or incinerated. In addition to mercury, fluorescent light bulbs contain aluminum, glass, and phosphorous, all of which can be recycled. Pasco County recycles 5,000 to 7,000 light bulbs annually. This translates to nearly 2,750 to 3,850 pounds of aluminum, glass, mercury and phosphorous, elements that can be re-used in the re-manufacturing of new products. Other benefits of this program are saving landfill space and protecting our environment. (light bulbs recycling htm 2002)

2.5 Processing Recycled Glass

Today, beneficiation plants or processing facilities are owned and operated by third parties but may be located at glass manufacturing plants. These facilities require a constant supply of color-sorted cullet from which they remove contaminants such as paper, plastic, and metal, or other glass/ceramic items before crushing the glass. The

single greatest problem for recyclers and glass manufacturers alike is the risk of contamination. The recycler does not want to ship, nor does the manufacturer receive glass that is contaminated with undesirable materials. Contaminated cullet decreases quality and increases costs for everyone. Thus, contaminated cullet can not be recovered, container glass stream may be ceramic (such as coffee mugs or dinnerware), metal, gravel and dirt, or non container types of glass (such as window glass or Pyrex) mixed in with the cullet. Metals are removed magnetically. Light items such as loose paper or plastics are removed by vacuum. Contaminants are a risk to the glass manufacturer and disrupt production, produce defective glass, and damage glass manufacturing equipment. Virtually all glass food and beverage containers including food jars, beer bottles, wine and liquor bottles, and juice containers are recyclable. On the other hand, household glass products such as light bulbs, drinking glasses, and window panes are unacceptable for producing new glass containers. Varying chemical compositions and different melting temperatures of these types of household glass products generally cause defects in the new containers (ISRI 2001).

2.5.1 *Cullet Quality*

Recycled materials are industrial feedstocks. Industrial feedstocks, whether they are recycled or "virgin," must meet quality specifications. The glass container industry does not use amber or green glass to make clear containers, for example. Therefore, glass used for recycling must be contaminant free.

The glass container industry and its suppliers continue to invest significant resources into improving glass processing and recycling technologies. These innovations include automated color separation, mechanized ceramic sorting, organic colour coating and cullet pulverization technologies. The industry is experimenting with using more green cullet in amber glass batches to increase recycled glass usage. Member companies also continue to develop ways to increase the use of three colour mixed glass.

GPI believes the best way to collect all recyclables is through curbside collection and sorting. Curbside separation of recyclables by the collector will deliver to all user industries the greatest amounts of high quality recyclables.

2.6 Glass Recycling Methods

Waste glass can be put to new use in ways, which include the following;

- By reusing it for its original purpose
- By altering the principal item to make new products
- By using it as cullet in the manufacture of new glass
- By using it as a substitute for a raw material
- By using it as a raw material in a newly invented product

2.6.1 *Reuse*

The most direct method of making use of waste glass is to return to its original purpose. Flat glass or tubing can be salvaged, cleaned, perhaps cut and placed back in service, example cutting window- panes from large sections of broken glass. Glass containers can be returned to the bottler for refilling. The only problem with this method is adequate

cleaning because sometimes consumers use these containers for storing insecticides and their likes.

2.6.2 *Alterations*

Sometimes glass containers and other objects can be made into new useful or novelty items. Bottles can be cut to make drinking glasses, funnels, candle holders, vases and so on. Other examples include the use of recycled fluorescent light bulbs as tubing in manufacturing solar water heaters, burnt out incandescent light bulbs have been used to make beakers, and specimen dishes. Glass bottles can be cut with an electric wire, ordinary glass - cutter or by wrapping them with a string and burning the string (Ott 1986).

2.6.3 *Cullet*

The recycling of glass primarily of glass containers has become an integral part of the glass production industry. Manufacturers buy back whole and broken glass containers to make new glass containers for a wide range of products, with no loss in quality or structural integrity. When considering the possibilities of using cullet, first of all you have to determine your requirements for the raw materials. These in turn are determined by the requirements of the finished product (Stotzel 1997).

The glass recycling process begins with the collection of used bottles and other containers. Generally the glass is first separated by colour into flint (clear), green, and amber (brown) and cleaned. The glass containers are then crushed into small pieces

known as cullet, which is used by manufacturing plants to produce new glass containers. This material is known as processed or furnace ready.

Container glass is usually the most suitable kind of glass for use as cullet, because its composition tends to be essentially the same from manufacturer to manufacturer. The primary market for cullet is the manufacture of bottles and jars for packaging food, other glass objects made from cullets include handicrafts, fibre -glass, vases and beads.

New glass bottles maybe made with up to 100% cullet. However the actual percentage depends on the quality and quantity of cullets available.

There maybe some energy savings in using cullet in glass manufacture, but the savings depends on the percentage of cullets used. Using cullets however does save resources. Each tonne of cullet saves 1.1 tonnes of raw materials (Ott 1986).

2.6.4 *Glass as a substitute for a raw material*

Concrete contains a substantial quantity of aggregate, especially crushed stone. Low alkali glasses can be substituted for much of the crushed stone. Thousands of tons of unsalable coloured glasses are used as aggregates in concrete thus solving the problem of waste disposal.

Recycled glass is similar in composition to feldspar, a naturally occurring material and a common component of the clays used in making ceramic products. Consequently, glass can be added in varying amounts to most ceramic products. Studies have shown that face brick can be produced on a commercial scale without difficulty. Similar studies have

shown that recycled glass can be substituted for feldspar in porcelain bodies, tile bodies, and decorative artificial stone (Ott 1986).

2.6.5 *Glass as a Raw Material in New Products*

The most promising approach is to find a process for which glass is the most suitable raw material, to do this, you need to understand the basic vitreous inorganic nature of glass, and take advantage of it to create a unique product that meets a need of the local market. The creation of inorganic foams is an excellent example of this approach. The process requires glass as a starting material and there are no natural minerals that can be substituted for the glass. The resulting products have distinct advantages over competing products in the market place.

When glass is mixed with a foaming agent that gives off its gas at the same temperature at which the glass softens, that gas will cause the glass to foam. The result is a product that can be used for thermal and acoustical insulation. One version of foamed glass is made by crushing waste glass to a uniform fine particle size, and then mixing it with bentonite, calcium carbonate, and water. The pressed mixture is then placed in a furnace where it foams. The finished product resembles a slab of polystyrene foam except that it is rigid. It is fire proof, impervious to water or acidic damage and can be easily cut with a saw. Several different foaming agents have been used in this process. Cow manure is the most common foaming agent (Ott 1986). There may be a number of other applications of this type. It takes imagination and an understanding of glass to invent a product that is appropriate for a given place.

2.7 Cullet for Manufacture of New Glass

There are different processes for the utilization of cullets for manufacture of new glass. These processes include remelting and sintering

2.7.1 *Re-melting*

Cullets can be used as crushed to be remelted in pots or furnaces for use to make new products.

2.7.2 *Sintering*

Sintering is a local welding at the points of contact between particles followed by diffusion along the surfaces and in the bulk (Alexander et al 1997). The degree to which solid state sintering contributes to overall densification depends on the several factors including surface energies, solubilities, diffusivities and particle sizes (Randall et al 1996), this method involves the use of powders. The characteristics desired in a powder are largely dictated by the properties required of the product (Williams 1963). The demand for impermeability therefore makes severe calls on the control of the sintering process and hence on the nature of the powder itself. All the detailed mechanisms of sintering predict that sintering rates will increase with decreasing particle size, other things being equal (Williams 1963).

In the sintering process three stages are distinguished. In the early stage necks are formed between the particles, in the immediate stage the pores are still connected by channels

along edges where three grains meet and the final stage only isolated pores are present. In all the stages the driving force of the process is the surface energy of the pores in the first stage.

In the first stage, surface diffusion may be an important mechanism but in later stages the most important mechanism is the diffusion of vacancies from the pore surface to the grain boundaries and other vacancy sinks (Hornstra 1963).

By these mechanisms many sintering experiments can be explained at least qualitatively. However several complications may prevent a quantitative agreement between experiment and theory. One of these complications is the fact that grain growth occurs during sintering and lowers sintering rate, because the diffusion path of the vacancies become longer. A second complication is presented by the role of vacancy sinks, other than grain boundaries. The third complication arises from the fact that not all pores have the same size distribution. (Hornstra 1963) So that the number of pores decreases long before complete density is attained and the overall sintering rate depends on the pore size distribution. There has been interest in recent years in development methods for enhancing densification and controlling micro- structure evolution during powder processing of ceramics and composites. Many approaches have been used to increase sintering rates, achieve high relative density and avoid pores and other large flaws in the final micro- structure (Sacks 1992).

2.7.2.1 *Particle Size Selection*

Powder size and size distribution can have marked effect on the final structure produced as well as factors such as compacting density, efficiency and consolidating time. A reduction in particle size increases the driving force and reduces the mass transport distance for densification and achieves finer grain size in the sintered micro- structure (Sacks et al 1992). There is evidence that powders consisting of uniform spheres can yield high density ceramic materials at lower sintering temperatures (Matijevic 1992). A suitable particle size range for many powder processing methods is 0.1 – 1.0mm.

2.7.2.2 *Forming methods*

The forming methods involved in the sintering of these waste glasses include Dry Pressing and Slip Casting. Shrinkage and shape distortion of powder compacts during sintering is assessed by the heating microscopy technique. Available theoretical models for the sintering of composite materials are to be adapted for the particular problem of glass and ceramic matrix composites with graded composition and the results compared with the experimental data.

2.7.2.3 *Sintering temperature*

In common with all diffusion controlled processes, sintering proceeds much more rapidly at temperatures above half the absolute melting point of the materials concerned (Alexander et al 1997). However the sintering temperature of any glass powder is dependent on a lot of factors so a fixed temperature value cannot be given. Such factors

are particle size, composition, softening point of parent material, the heating rate, method of compacting and so on.

Expected sintering temperatures for some glass types are as follows;

Glass Type	*Softening Temp.*	*Expected Sintering Temp.*
Soda Lime Glass	700 ^{o}C	750- 850^{o}C
Boro-Silicate Glass	820 ^{o}C	880-920 ^{o}C
Lead Glass	630 ^{o}C	680-730 ^{o}C

The glass powder compacts can be fired for about six hours at one hour interval at the expected sintering temperature range, after a holding time of 4 hours (Boccaccini et al 2000).

CHAPTER 3

MATERIALS AND METHODS

This study sought to convert the glass waste of Light tubes and window glass (soda- lime silica glass), drinking glass (lead crystal glass) and laboratory glass (borosilicate glass) to functional forms using the sintering method.

3.1 Materials

3.1.1 *Samples Procurement from Zaria, Nigeria*

Samples were procured initially from Zaria, Nigeria to conduct the preliminary test from a window glass shop in Sabon Gari Zaria, Ahmadu Bello University student hostels, Ahmadu Bello University Senior Staff Club and glass blowing laboratory at the Department of Industrial Design for window glass, fluorescent tubes, drinking glasses and laboratory glass ware respectively.

Table 3.1: Inventory of Waste Glass Collected in Zaria

Type	Weight in Kg	% of total waste
Drinking Glasses	7 .5	8.36
Fluorescent Tubes	25.2	28.09
Laboratory Glass	6.7	7.47
Window Glass	50.3	56.08
Total	89.7	100

Some of these glasses were washed and crushed to powders by stamping in order to obtain fine sized particles. The glass sample powders were sieved to obtain particle sizes in the size range 0.1- 1.0mm, constituting four batches of each type of glass drawn from the mesh sizes of 425, 300, 212 and 150 microns making a total of 16 samples labeled as thus;

	a	b	c	d
1. Drinking Glass	425	300	212	150
2. Fluorescent Tubes	425	300	212	150
3. Laboratory Glass	425	300	212	150
4. Window Glass	425	300	212	150

The powdered glass samples (1a – 4d) were mixed with sodium silicate as binder in concentrations of 5, 10, 15 and 20% to provide the necessary strength when handling the cast pieces before firing. Cylindrical compacts of 15mm in diameter by 10mm were

formed by compression of the composites in a die by hand. The samples were fired in an electric kiln at their expected sintering temperature range. Sample 1 was fired to 800^{o}C and maintained at this temperature for one hour, two hours, three hours and four hours soaking time consecutively. This was repeated for samples 2, 3 and 4 at sintering temperatures of 750^{o}C, 900^{o}C and 720^{o}C respectively. The preliminary tests were conducted at Ahmadu Bello University Zaria to determine the sinterability of the glasses, See appendix 1 for the microstructure of some of the compacts.

3.1.2 *Sample Procurement from Houghton Michigan*

Another set of samples of similar compositions to those used for the pilot study were procured from the Houghton area in Michigan USA. Window glass was collected from Doors and Windows Calumet, fluorescent tubes were obtained from the IMP building as well as the laboratory Glass from laboratories in the Mineral and Materials Engineering Building and drinking glass (broken) were collected from the restaurant in down town Houghton. The glasses collected were washed dried, hand broken and weighed (See table 3.1.2).

Table 3.2: Inventory of Waste Glass Collected in Houghton Area

Type	Weight in Kg	% of total waste
Drinking Glasses	6.5	13.98
Fluorescent Tubes	6.3	13.55
Laboratory Glass	10.7	23.01

Window Glass	23	49.46
Total	46.5	100

3.1.3 *Preparation of Powders*

The glass samples used in this study were fairly large pieces. They were crushed individually by passing them through a hammer mill. Using a hammer mill alone did not produce powders and so they were passed through a roll crusher to reduce their sizes further as depicted in table 3.1.2.1. The crushed samples were sieved (Tyler mesh) with the aid of a mechanical shaker and a shaking time of 20 minutes results of which is shown in table 3.1.2.2. It was quite evident from the preliminary sintering test that less than 150 micrometer grain size would be required for subsequent experiments meaning that only meshes 150 to -200 would be needed which amounted to only 4.94% drinking glass, 3.316% fluorescent tubes, 10.145% laboratory glass, 3.743% window glass and as such the lager grains were further ground in a rod mill. 1 kg of each glass sample ground for 1 hour in the rod mill produced 50 -60% glass particles within the size range of -75 to 106 microns.

Table 3.3 Glass Powder Processing

Type	Hammer mill	Roll Crusher
Drinking Glasses	Passed through once	Passed through once
Fluorescent Tubes	Passed through once	Passed through 5 times
Laboratory Glass	Passed through once	Passed through once

Window Glass	Passed through once	Passed through once

Table 3.4 Glass Size Distribution (% wt retained on sieves of MTU collection)

Type of Glass	Drinking Glass	Fluorescent	Laboratory	Window
A	2.683	7.303	13.340	6.922
B	9.513	6.041	11.181	5.756
C	5.229	3.419	8.673	3.362
D	4.165	2.454	6.954	3.056
E	2.449	1.470	3.937	1.795
F	1.672	1.290	4.555	1.811
G	0.819	0.556	1.653	0.137
H	68.928	76.937	49.701	77.148
Total	100	100	100	100

Tyler mesh (microns)

A – Mesh 40 (425)

B- Mesh 50 (300)

C- Mesh 70 (212)

D – Mesh 100 (150)

E – Mesh 150 (106)

F – Mesh + 200 (75)

G – Mesh -200 (-75)

H – Mesh +20 large grains

3.2 Chemical Analysis

The glass samples were analyzed using a Leeman Labs PS950 Inductively Coupled Plasma Spectrometer (ICP) to determine their chemical composition. They were digested using the acid/flux solution procedure. 200 mg glass sample was added to 1.2 g of lithium- metaborate and heated to 950^{o}C for 20 minutes and poured into 250 mls of 10% nitric acid and 10% hydrochloric acid. The samples were scanned then using a Leeman Labs PS950 Inductively Coupled Plasma Spectrometer (ICP). The following elements were examined as primary components and they include Silicon, Sodium, Calcium, Magnesium, Aluminium, Iron, Potassium, Titanium, Manganese, Lead, trace elements included Barium, Cerium, Chromium , Copper, Zirconium and Arsenic .

3.3 Particle Size Selection

The preliminary sintering test showed that finer grain of 150 microns had closer compaction and were better fused on firing, therefore the next mesh to that of 106

microns and the least grain size of less than 75 microns were taken from each sample to produce the powder compacts with the hope of achieving better compaction and more full density on fusion.

3.4 Forming

Trials of the following compositions were made for each type of glass to find out which glass particle size plus matrix content would result in the best compact. The –75 microns glass powder was used to form the matrix while sodium silicate and bentonite (5% water was added) were used as the bonding agents.

Compositions

Sample % (106 microns)	70	60	50	40	30
Matrix % (-75 microns)	30	40	50	60	70

5% volume of binder was added co nsecutively as the bonding agent. 10g of every sample was weighed each time and pressed with a uniaxial press, forming three sets of compacts. The first containing no binder pressed at 5,000 psi and 10,000 psi, the second set contained binder pressed at 5000 psi and the third set contained binder and also pressed at 10,000 psi. The compacts pressed at 5,000 psi were 29mm in diameter and 10 mm thick while those pressed at 10,000 psi were 29mm in diameter and 9mm thick. One minute was allowed for the compacts during forming in the press before releasing it out.

3.5 Drying

The pressed pieces were left in the open on trays over a period of 24hrs to dry at room temperature of 21^{o}C.

3.6 Sintering

A set of samples were fired in an electric kiln at the following temperatures 600^{o}C, 650^{o}C, 700^{o}C, 750^{o}C and 800^{o}C with holding time of two hours. 700 -750^{o}C was determined as a suitable sintering temperature range and as such the subsequent samples were sintered within this temperature range at 700^{o}C, 725^{o}C and 750^{o}C.

3.7 Property Test

The American Standard Test Method (ASTM) was used to test for some of the properties required to determine the status of the sintered recycled glass powder compacts. The drying and firing shrinkages were measured according to the ASTM C 326, weight, size, warpage, absorption were determined according to ASTM C 67 and compressive strength was measured according to ASTM C 773 - 88. Additional imperviousness test for glazed ceramic facing tile as specified in specification C126 was also carried out on some of the samples. The microstructures of specimens were observed using a JEOL JSM 820 Scanning Electron Microscope (SEM).

3.7.1 *Drying and Firing Shrinkages*

This test covers the determination of linear shrinkage of ceramic whiteware clays, both unfired and fired. Test specimens were dried and then placed in a drying oven at a temperature of 100^{o}C to 110^{o}C and further dried for 24 hours. The specimens were then

fired to a firing schedule as stated in sintering. The linear shrinkage after drying and firing were calculated respectively with the formulae

$$S_d = \frac{L_p - L_d}{L_p} \times 100$$

Where

S_d = linear drying shrinkage, %

L_p = plastic length of test specimen

L_d = dry length of test specimen

And

$$S_t = \frac{L_p - L_f}{L_p} \times 100$$

Where

S_t = total linear shrinkage after drying and firing, %

L_p = plastic length of test specimen

L_f = fired length of test specimen

3.7.2 *Weight Measurement*

A mettler balance was used to weigh dry full size fused compacts from each sample. The weight of each sample was measured to the nearest 0.05mm

3.7.3 *Measurement of Size*

A steel rule graduated in metric was used for measuring, the diameter and length of all dry and fused samples were measured to the nearest 0.05mm.

3.7.4 *Measurement of Warpage*

The measurement of warpage required the use of steel rule or measuring wedge to measure the warpage, where there is greatest departure from straightness, there was no need to conduct this test since none of the fused compacts showed any warpage.

3.7.5 *Measurement of Absorption*

The samples were dried, cooled and weighed. Each specimen was then submerged in distilled water at 21^{o}C for the specified time (5hours and 24 hours). The specimen was removed and its surface wiped off with damp cloth and weighed again and weighing was completed in not more than 5 minutes after removing it from the bath. The absorption of each sample was calculated as follows

Absorption % = $100(W_s - W_d)/W_d$

Where

W_s = Saturated weight of specimen after submersion in cold water

W_d = Dry weight of specimen

The specimens that were used for the cold water test were returned to cold distilled water and subjected to the boiling test of 1 hr, 2 hr and 5 hrs. The specimen was placed in the bath such that water circulated freely on all sides of the specimen. The water was heated to boiling within an hour and was left to continue boiling for the specified time, then cooled to 21^{o}C by loss of heat. The specimen was removed wiped with a damp cloth and weighed. Weighing was also completed within 5 minutes after taken the specimen out of the water. Absorption of each specimen was calculated as thus;

Absorption % = $100(W_b-W_d) /W_d$

Where

W_d = Dry weight of the specimen

W_b = Saturated weight of the specimen after submersion in boiling water.

3.7.6 *Measurement of Compressive Strength*

Instron 4468 was used for the test. Samples were made of the ratio 1:1 of length to diameter, the ratio desired is 1.9 and not more than 2.1. It was possible to produce only ratio 1:1 with the uniaxial press available. In conducting the test single sample and 2 samples together were used to find out any significant difference resulting from the different sizes. A loading rate of 50KN/min was applied and a crush head speed of 12mm/min except for the first sample from fluorescent tube of 25mm/min were also applied

3.7.7 *Imperviousness Test*

Permanent blue black fountain pen ink was applied liberally to glazed surface of the specimens and allowed to remain for 5 minutes. The surface was washed with wet cloth and running water and it was examined from a distance of 1.52 m for staining of the finish.

3.7.8 *Microstructure*

The microstructures of specimens were observed using a JEOL JSM 820 Scanning Electron Microscope (SEM). The microstructures of the some compacts fused at 700^{o}C

and 750^{o}C of only the samples containing 5% bentonite as binder and pressed also at 10,000 psi were taken. Some sections were also analyzed to give the chemical composition at such points that would help explain the chemical reactions at those points.

CHAPTER 4

RESULTS

4.1 Chemical Analysis

Table 4.1 Chemical Analysis of glass samples.

Element (%)	Drinking Glass	Fluorescent Tube	Laboratory Glass	Window Glass
As	X	X	X	X
Cr	X	X	X	X
Zn	0.031839	0.014859	0.009804	0.012535
Pb	X	X	X	X
Si	19.35638	24.82943	28.1285	18.10751
Mn	0.004101	0.005112	0.007584	0.006386
Fe	0.155946	0.177364	0.245554	0.186742
Mg	0.683146	1.768664	0.146894	1.571336
Al	0.599458	0.638553	0.827252	0.198603
Cu	0.036763	2.062067	0.041526	0.102708
Ti	0.010815	0.009951	0.033998	0.01262
Zr	0.014385	0.016454	0.019124	0.015152
Ca	5.433759	2.729423	6.537418	5.808848
Ce	0.047803	0.001984	0.015477	0.006264
Ba	0.002583	0.002838	0.015571	0.003216
Na	8.704792	11.46128	9.724909	9.553753
K	X	2.842764	2.339499	X

The Chemical analyses were performed to establish the chemical compositions of the samples as basis to explain the effect of chemical content of glass on sintering as well as to illustrate the safety of recycling the glass wastes into floor tiles. All samples for instance did not contain lead and this suggests that they are safe to be used for floor tiles since lead is considered a poison. All samples have a good amount of Sodium normally present in the form of the oxide, Sodium oxide has a fluxing effect on the glass composition this can explain why glass composites without any binder and those containing sodium silicate began sintering at temperatures as low as 600^{o}C.

4.2 Forming, Drying and Sintering

All compacts made except the compositions without binder were handled without chipping or breaking. Extra care had to be put in handling the ones that had no binder making them not a suitable composition but on drying they acquired some dry strength enough to warrant handling small pieces. The open air drying was sufficient for subsequent handling of the compacts.

During the sintering process, samples containing no binder began fusing at 600^{o}C and showed melting at 700^{o}C, those with sodium silicate as binder started fusing at 650^{o}C and when taken to temperature above 700^{o}C expansion and shape distortion occurred (appendix 2). Sintering temperature range of 700-750^{o}C was found suitable for composites containing bentonite as binder. The samples sintered at 750^{o}C were very hard and they developed a thin layer of glazing, making it possible to produce a glazed tile all in one process.


x


y

Plate 4.2a Window glass compact containing no Binder

Plate 4.2a shows compacts x and y from window glass containing 70/30 of coarse to fine grains and no binder, X was pressed at 5,000 psi while y was pressed at 10,000 psi. Both compacts depicted chipping at their edges. All samples that did not contain any binder and also pressed at 5,000 psi and 10,000 psi exhibited similar characteristics. They required to be handled with extra care.







Plate 4.2b Drinking Glass compacts containing Bentonite as Binder

Plate 4.2b shows the compacts from drinking glass sintered at 700, 725 and 750^{o}C respectively. The sintering results did not reveal any significant difference as regards the varying ratio of coarse to fine grains that they contained.



Plate 4.2c Fluorescent Tubes Compacts containing Bentonite as Binder

Plate 4.2c shows compacts made from fluorescent tubes sintered at 700, 725 and 750^{o}C respectively. No warpage was observed in any of the fired compacts. At 725^{o}C a thin layer of glaze was formed and its thickness progressed as the temperature was raised to 750 ^{o}C.



Plate 4.2d Laboratory Glass Compacts Containing Bentonite as Binder

Plate 4.2d shows compacts from Laboratory Glass sintered at 700, 725 and 750^{o}C respectively. No warpage was seen in any of the fired compacts. Glazing was seen only on compact that was fused at750^{o}C.



Plate 4.2e Window Glass Compact containing Bentonite as Binder

Plate 4.2e shows compacts from Window Glass sintered at 700, 725 and 750^{o}C respectively. No warpage was seen in any of the fired compacts. Glazing was seen only on compact that was fused at750^{o}C.

4.3 Shrinkage

One has to be able to predict the shrinkage behavior of a clay product during sintering to determine the proper size of mould or die to use so as to produce a predetermined size of fired ware. A lower shrinkage is always preferred if other properties can be achieved. Shrinkage is also an indication of physical and chemical changes or reaction between particles. Defects such as cracking and distortion may be introduced by inhomogenous shrinkage.

The shrinkage behaviour of the glass samples containing bentonite as binder at varying compositions sintered at 700^{o}C, 725^{o}C and 750^{o}C are shown in figures 4.3a, 4.3b, and 4.3c. In this discussion glass composition on the X axis of the figures represent the ratio of coarse to fine grain of 106 microns/-75 microns, 70/30 for instance represents 70% 106 microns glass grain and 30% -75 microns glass powder. Mean shrinkage is the

average of shrinkage in length and diameter. MS 1- MS 4 represent mean shrinkage of drinking glasses, fluorescent tubes, laboratory glass and window glass respectively.

4.3.1 *700^{o}C Sintering*

The shrinkage of the samples sintered at 700^{o}C is presented in figure 4.3a. Fluorescent tubes and window glass have greater levels of shrinkage. There was no significant difference in shrinkage among the varying compositions of the glass, meaning that no effect resulted from the high or low content of coarse glass. A similar observation was by drinking glass and laboratory glass except that drinking glass tile of composition 60/40 of coarse to fine grain showed a decrease in shrinkage likewise laboratory glass of 50/50 of coarse/fine grains.

4.3.2 *725^{o}C Sintering*

Shrinkage after sintering at 725^{o}C was higher as compared to the shrinkage at 700^{o}C. Sintering shrinkage is mainly determined by sintering temperature, particle size, and packing density. Higher temperatures give rise to better kinetics for atom diffusion to reduce the larger surface area of finer particles. Higher sintering temperature normally leads to higher shrinkage. The shrinkage of Laboratory glass composite increased and then decreased as the fine grain was raised to 70%, exhibiting the least shrinkage (See figure 4.3b)

4.3.2 *750^{o}C Sintering*

At 750^{o}C there was further increase in shrinkage and the explanation given for the sintering temperature of 725^{o}C is applicable here also. Figure 4.3c show the sintering results of the samples fired at 750^{o}C. Compacts from drinking glass shrank the most from compositions 60/40 and 50/50 and then there was a decrease in shrinkage as the percentage of fine glass powder in the composition increased. Fired compacts from fluorescent tubes and laboratory glass showed the same amount of shrinkage for all composites, while compacts from window glass exhibited the least shrinkage for 70/30 and 60/40 composites.

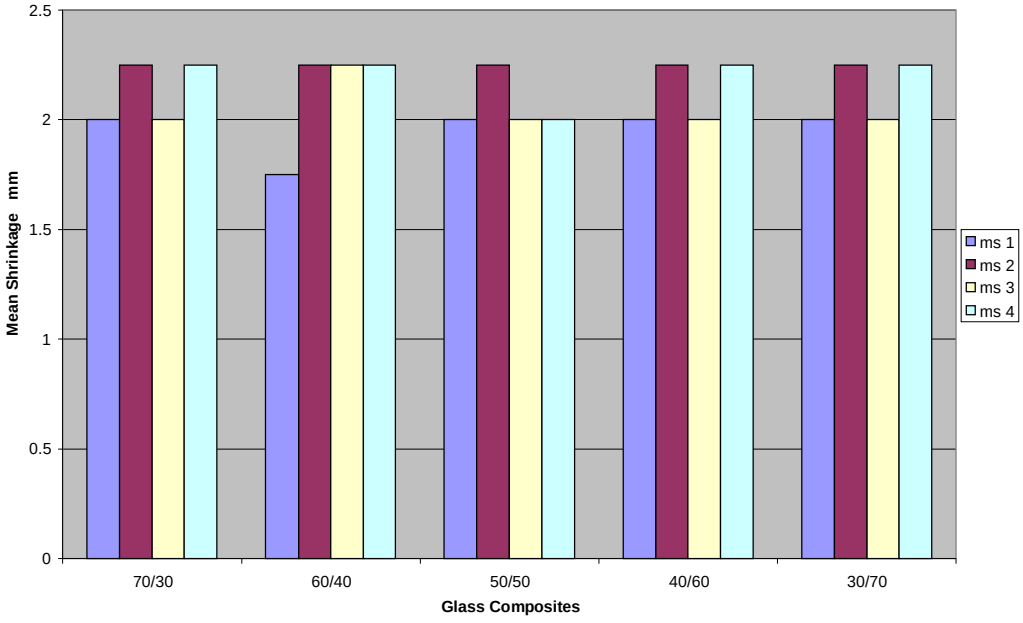


Figure 4.3a Firing Shrinkage for Compacts Sintered at 700^{o}C

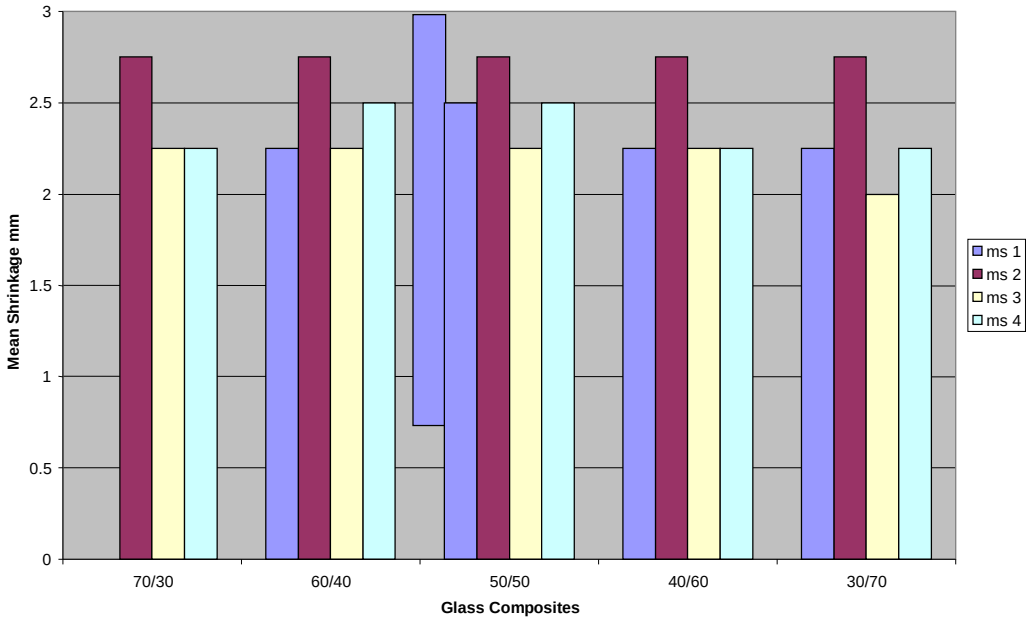


Figure 4.3b Firing Shrinkage for Compacts Sintered at 725^{o}C

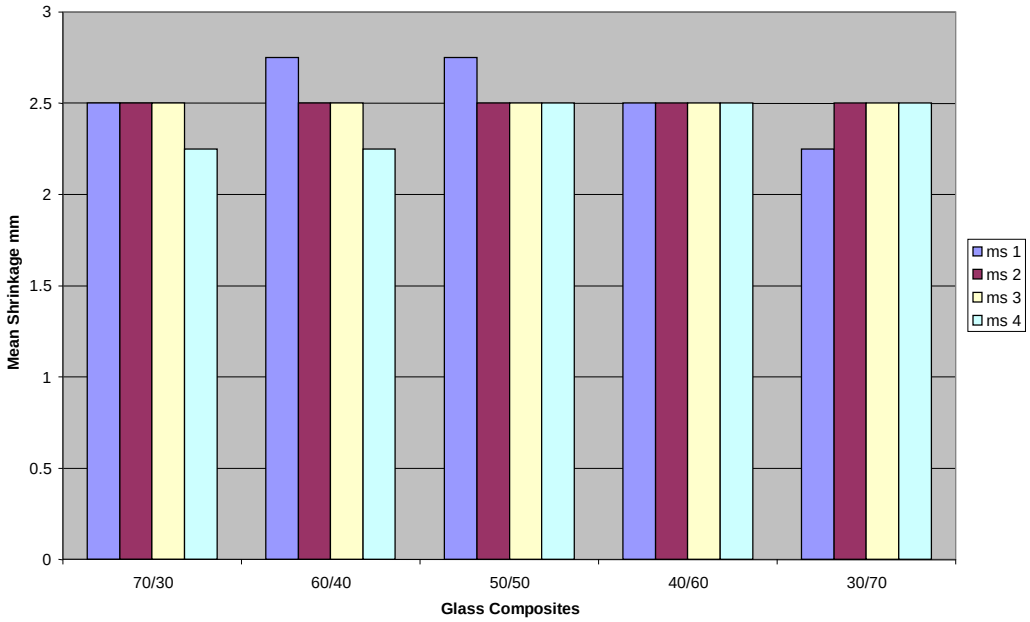


Figure 4.3c Firing Shrinkage for Compacts Sintered at 750^{o}C

Shrinkage factor which is used to convert fired sizes to plastic sizes or mould sizes can be calculated as follows:

Shrinkage factor = L_p/L_f

Where L_p = plastic length of test specimen and L_f = fired length of test specimen.

D 60/40 has the least shrinkage after fusion at 700^{o}C of 1.75 and a drying shrinkage of 0. Its shrinkage factor would be 9/8 = 1.125. While D 60/40 fired at 750^{o}C has the highest shrinkage of 2.75 and a shrinkage factor of 9/7 = 1.286. The ASTM specifies a shrinkage factor from 1.09 to 1.14 as permissible shrinkage factor for tiles. All fired pieces that had a fired length of not less than 8mm fall within this range. There are fourteen of them sintered at 700^{o}C (table 4.3a in appendix 3), six sintered at 725^{o}C (table 4.3b in appendix 4) and one sintered at 750^{o}C (table 4.3c in appendix5). These samples also have a total linear shrinkage of 11.1 making them fall within the permissible range of the ASTM standard of 8.6 to 12.1

4.4 Warpage

The samples containing bentonite were the main focus and none of these samples showed any warpage or distortion.

4.6 Absorption

The effects of sintering temperature, glass type and glass particle size on water of absorption are illustrated in Figures 4.5a, 4.5b, 4.5c, 4.5d, 4.5e, 4.5f, 4.5g, 4. h, 4.5i and 4.5j, Figures 4.5a – 4.5d showed results of submersion in cold water while figures 4.5e – 4.5j show boiling tests results. In this discussion WA1 represents water of absorption for

drinking glass sample. WA2 represents water of absorption for fluorescent tubes, WA3 represents water of absorption for laboratory glass samples while WA4 represents water of absorption for window glass samples.

The water of absorption was higher at 24 hr absorption test for samples fused at 700^{o}C (table 4.5a, Appendix 6), laboratory glass L 30/70 had the highest water of absorption of 2.956% while fluorescent tube F 40/60 had the least water of absorption of 0%. The water of absorption was observed to decrease as the sintering temperature was raised to 725^{o}C and 750^{o}C (tables 4.5b and 4.5c Appendices 7 & 8). Boiling test of samples fused at 700^{o}C showed higher absorption rates and absorption increased with time of boiling (table 4.5d, Appendix 9). However as the sintering temperature was increased, absorption decreased (tables 4.5e and 4.5f, Appendices 10 & 11). Highest amount of water of absorption during the boiling test was by laboratory glass compact fused at 700^{o}C (L 30/70) of 4.149% at 1hour, 4.343% at 2 hours and 4.471% at 5 hours boiling. The maximum water of absorption allowed for an individual tile is 9% at 24 hour cold water absorption and 11% for 1 hour boiling absorption as specified in ASTM 212, it can therefore be said that all tiles made fall within the ASTM standards.

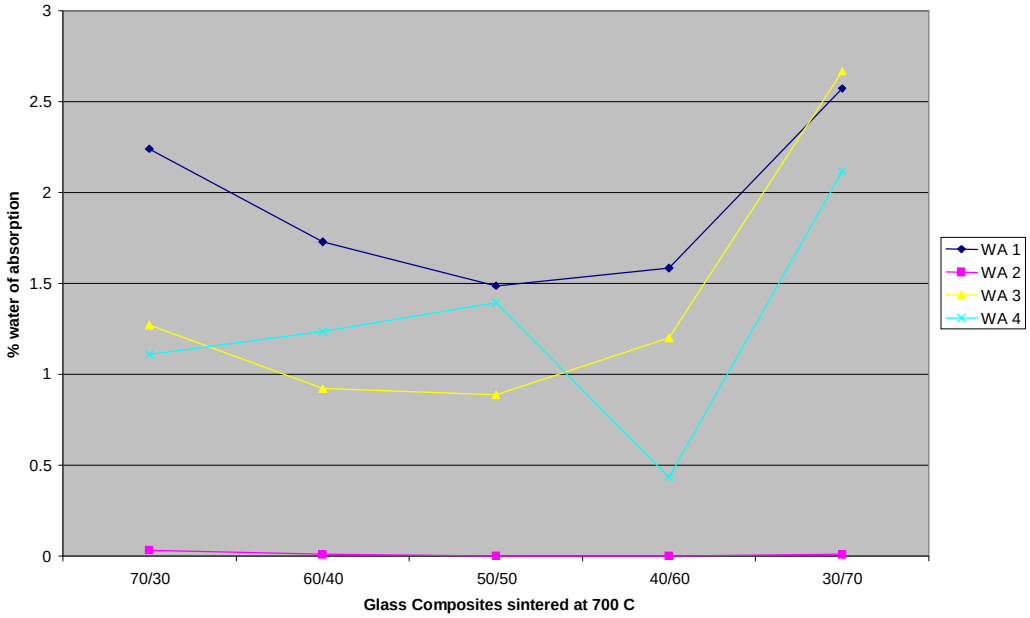


Figure 4.5a 5 Hour Water of Absorption for Compacts Sintered at 700^{o}C

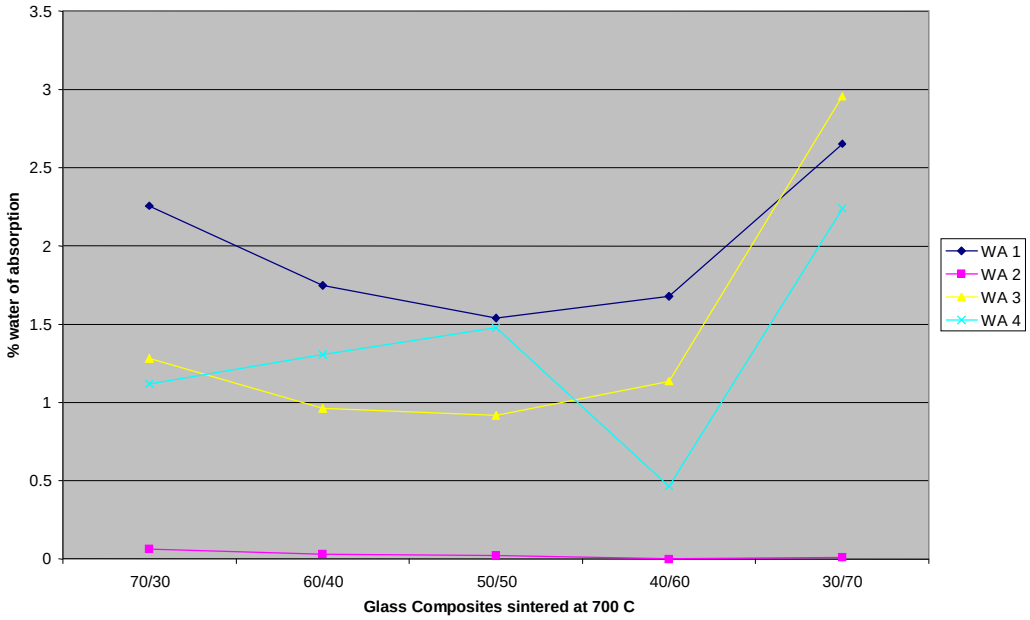


Figure 4.5b 24 Hour Water of Absorption for Compacts Sintered at 700^{o}C

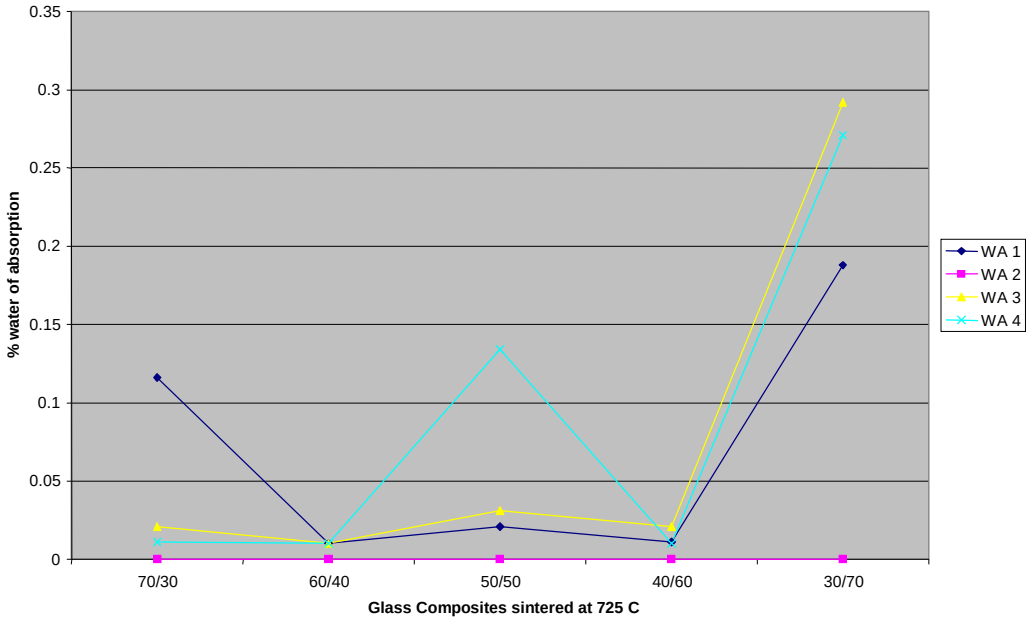


Figure 4.5c 5 Hour Water of Absorption for Compacts Sintered at 725^{o}C

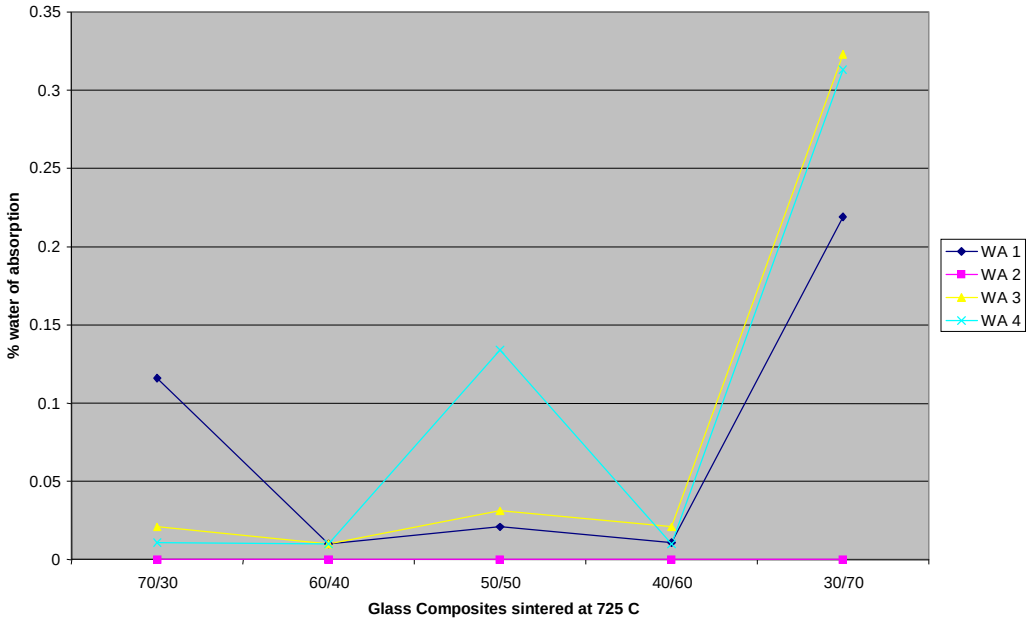


Figure 4.5d 24 Hour Water of Absorption for Compacts Sintered at 725^{o}C

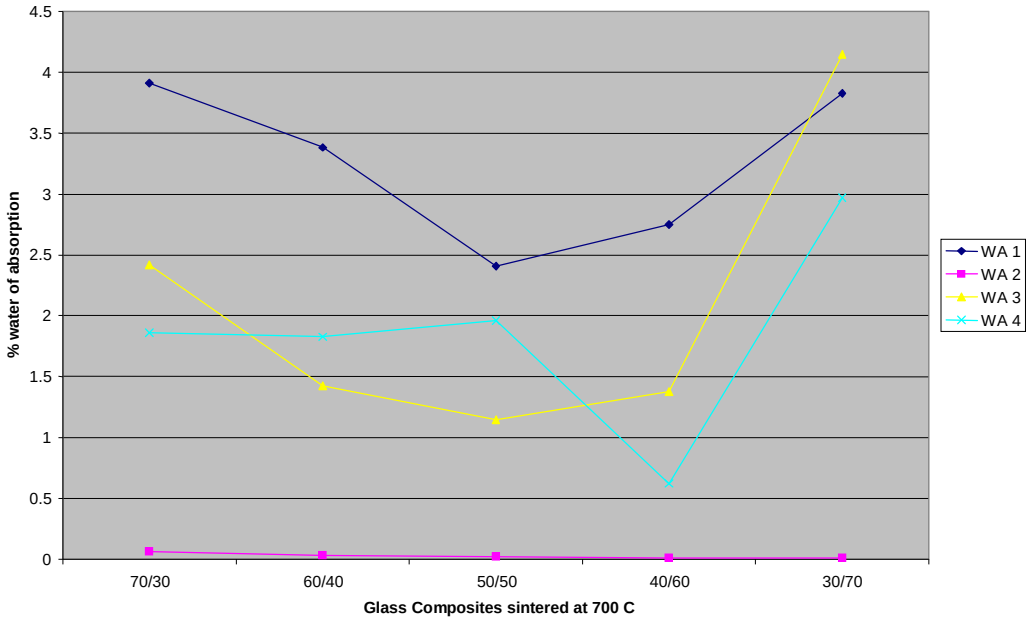


Figure 4.5e 1 Hour Water of Absorption (Boiling) for Compacts Sintered at 700^{o}C

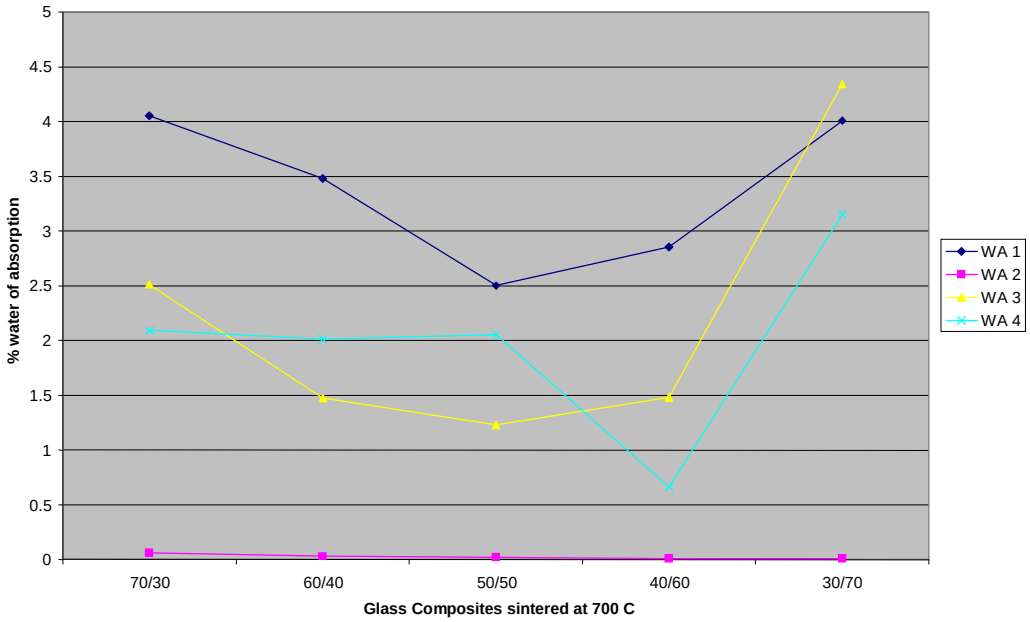


Figure 4.5f 2 Hours Water of Absorption (Boiling) for Compacts Sintered at 700^{o}C

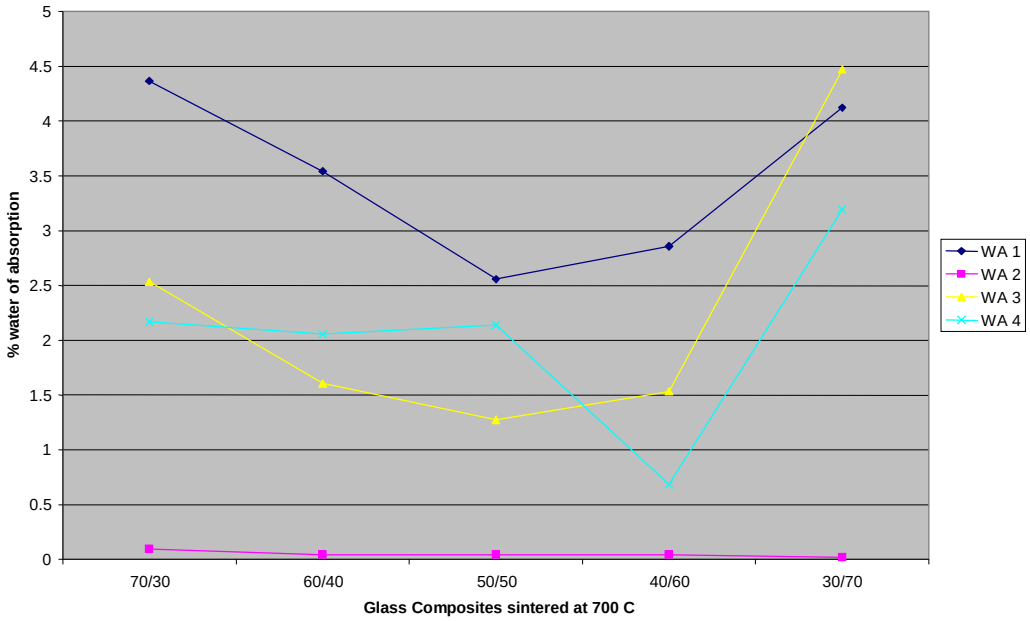


Figure 4.5g 5 Hour Water of Absorption (Boiling) for Compacts Sintered at 700^{o}C

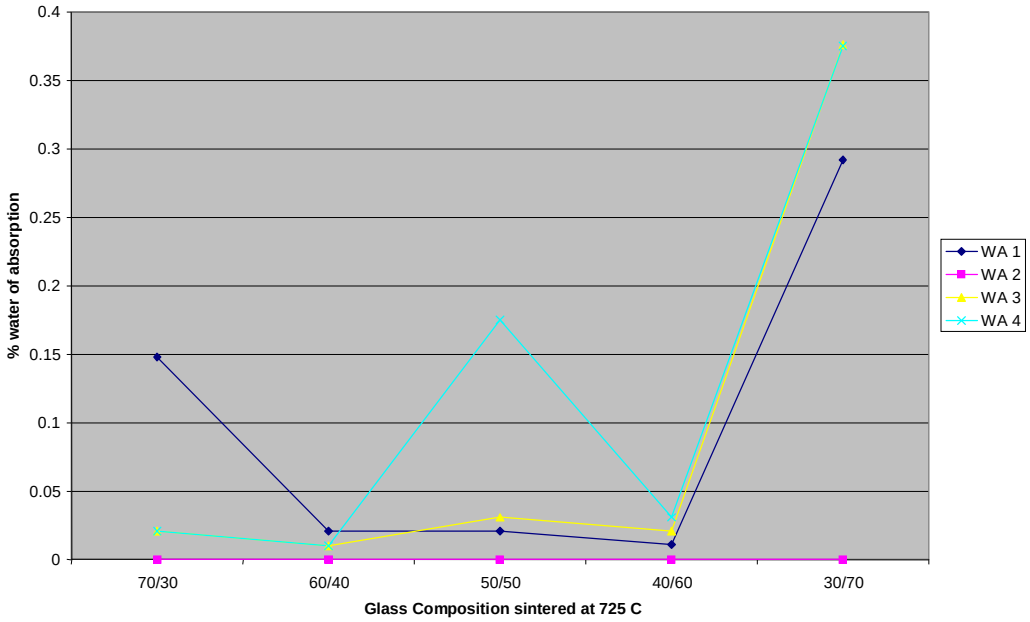


Figure 4.5h 1 Hour Water of Absorption (Boiling) for Compacts Sintered at 725^{o}C

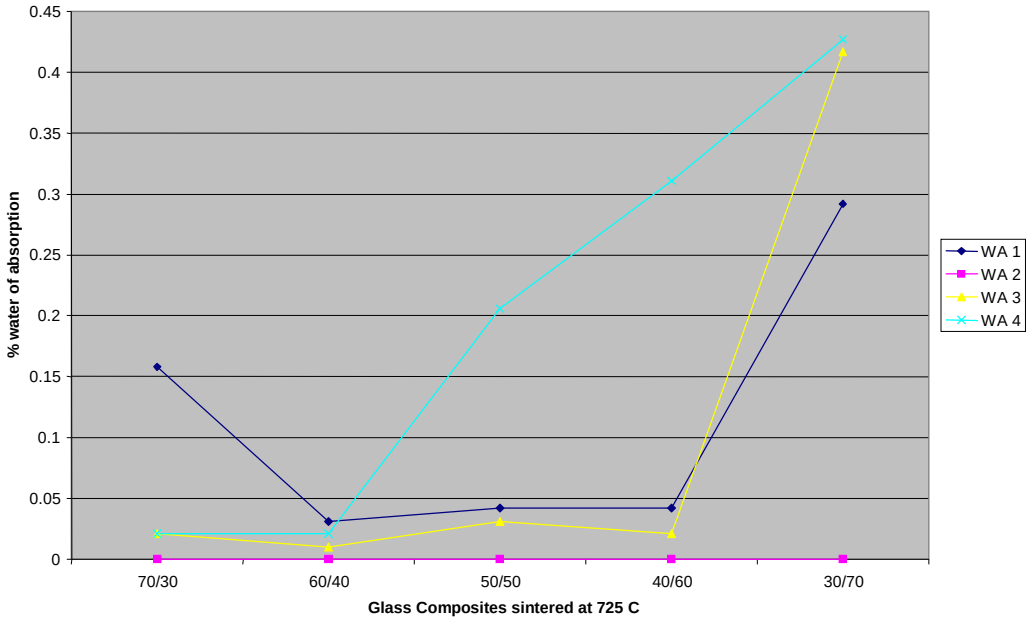


Figure 4.5i 2 Hours Water of Absorption (Boiling) for Compacts Sintered at 725^{o}C

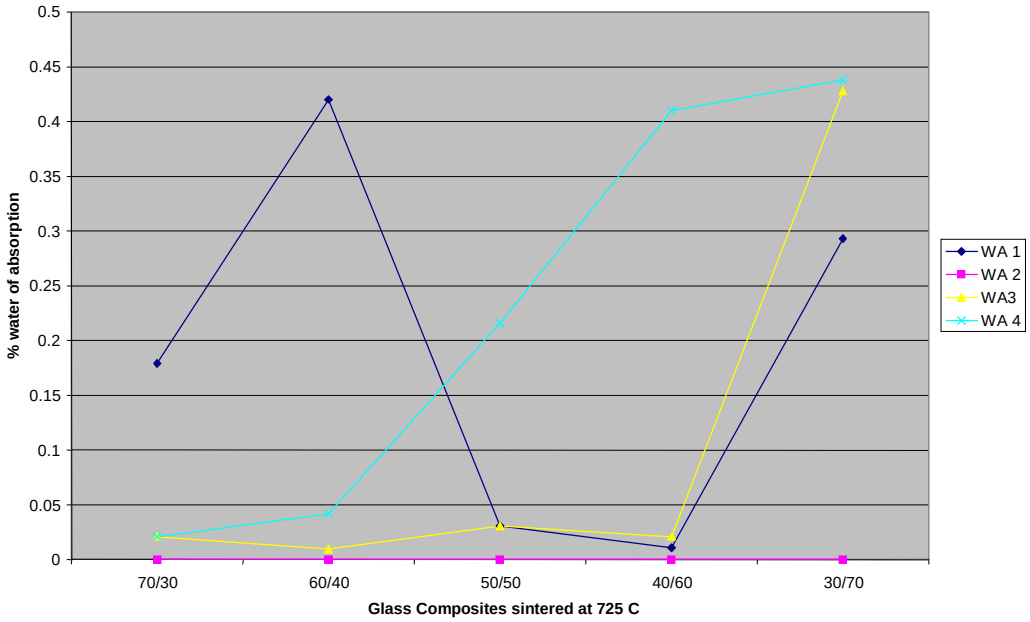


Figure 4.5j 5 Hours Water of Absorption (Boiling) for Compacts Sintered at 725^{o}C

4.6 Imperviousness

The samples that achieved glazing on the surface were tested for imperviousness, this included fluorescent tubes sintered at 725^{o}C and all samples sintered at 750^{o}C. No stain was seen from a distance of 1.5m thereby meeting the required ASTM specification. This glazing of the compacts was accidentally discovered and it is a positive development as it will help eliminate the glazing stage of the tiles since this can now be achieved all in one process thereby saving energy, time and materials. There would not perhaps be any need to duplicate effort in the development of a glaze that will fuse at a temperature as low as 750^{o}C while maintaining its qualities at the same time being compatible to the tile body.

4.8 Microstructure

The microstructures of the some compacts fused at 700^{o}C and 750^{o}C are shown in Figures 4.7a through 4.7q. The SEM is of only the samples containing 5% bentonite as binder and pressed also at 10,000 psi. Some sections were also analyzed to give the chemical composition at such points that would help explain the chemical reactions at those points. There was incomplete fusion of the some composites at 700^{o}C as is seen in the shape of the pores formed. However there was better fusion at 750^{o}C.

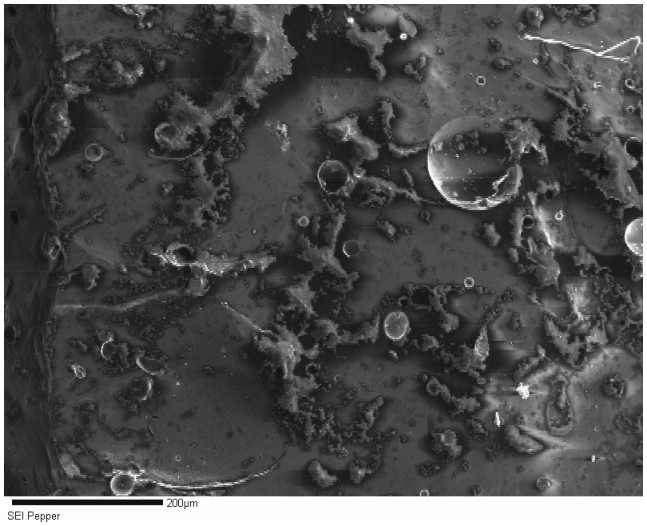


Figure 4.7a Drinking glass containing 30% 106 µ, 70% -75 µ and 5% Bentonite @ 750^{o}C holding time of 2 hrs

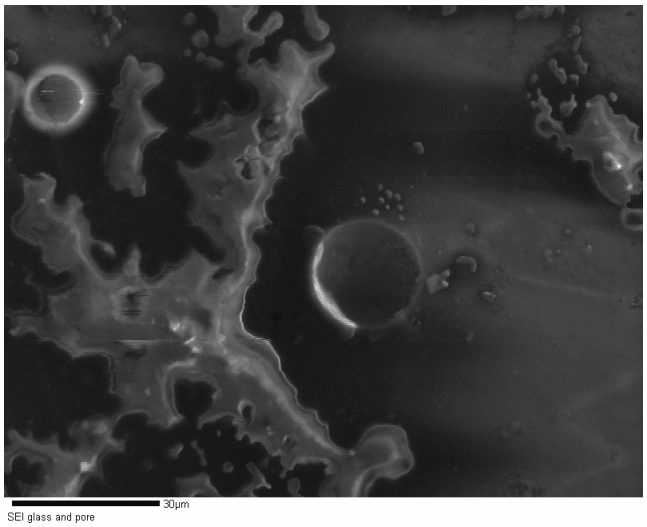


Figure 4.7b Drinking glass containing 30% 106 µ, 70% -75 µ and 5% Bentonite @ 750^{o}C holding time of 2 hrs

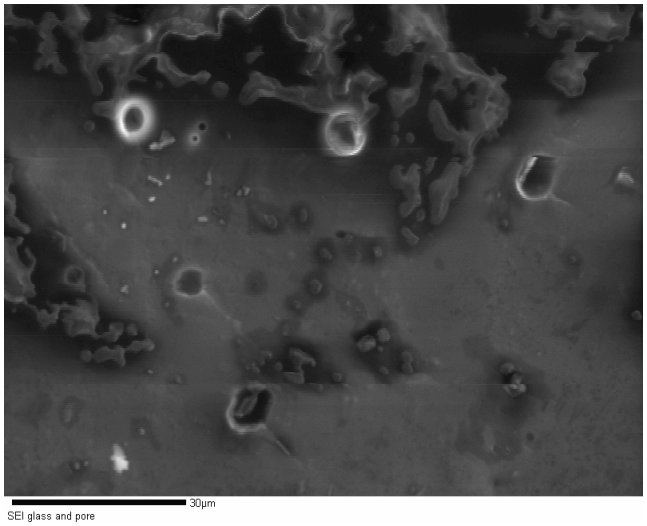


Figure 4.7c D1-2 - Drinking glass containing 30% 106 µ, 70% -75 µ and 5% Bentonite @ 750^{o}C holding time of 2 hrs

Figures 4.7a, 4.7b and 4.7c show the microstructure of sintered glass composite from drinking glass and 5% bentonite at 750^{o}C, this fracture was taken from towards the middle of the tile since its absorption indicated 0%. It became necessary to determine that the sample was absolutely pore free. The results in the three figures reveal that there were still some pores that have been encased by the glass matrix which was pore free thereby inhibiting absorption. The fracture structure also showed that there was chemical reaction as it was not possible to see bentonite particles, the structure was predominantly glass matrix. The pores are seen as the round features.

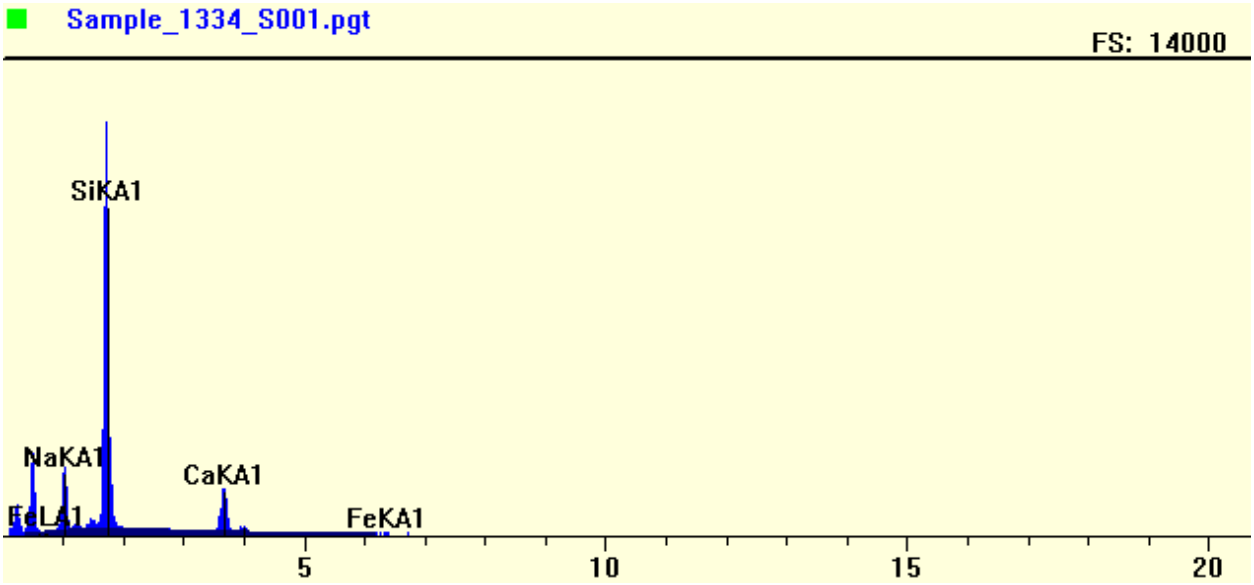


Figure 4.7a.1 Chemical Analysis of Drinking Glass Compact fused at 750^{o}C of area marked X

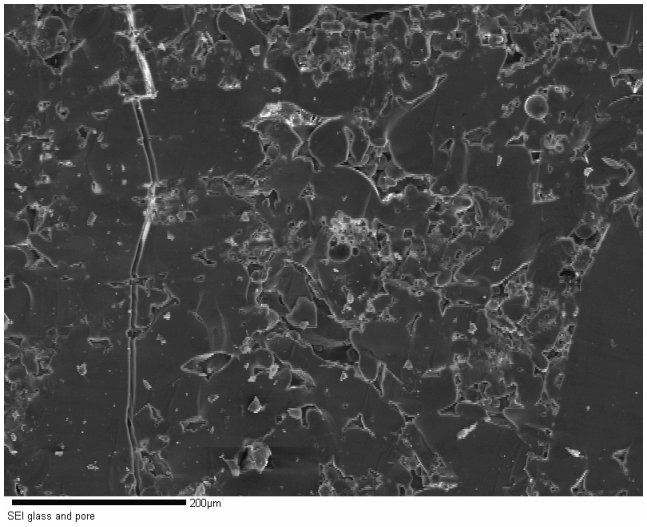


Figure 4.7d Drinking glass containing 40% 106 µ, 60% -75 µ and 5% Bentonite @ 700^{o}C holding time of 2 hrs

Figure 4.7d shows the microstructure of sintered glass composite from drinking glass and 5% bentonite at 700^{o}C. This fracture structure indicates that the glass particles were not completely fused and as such the pores are irregular in shape. Some bentonite particles are visible as the tiny white dots.

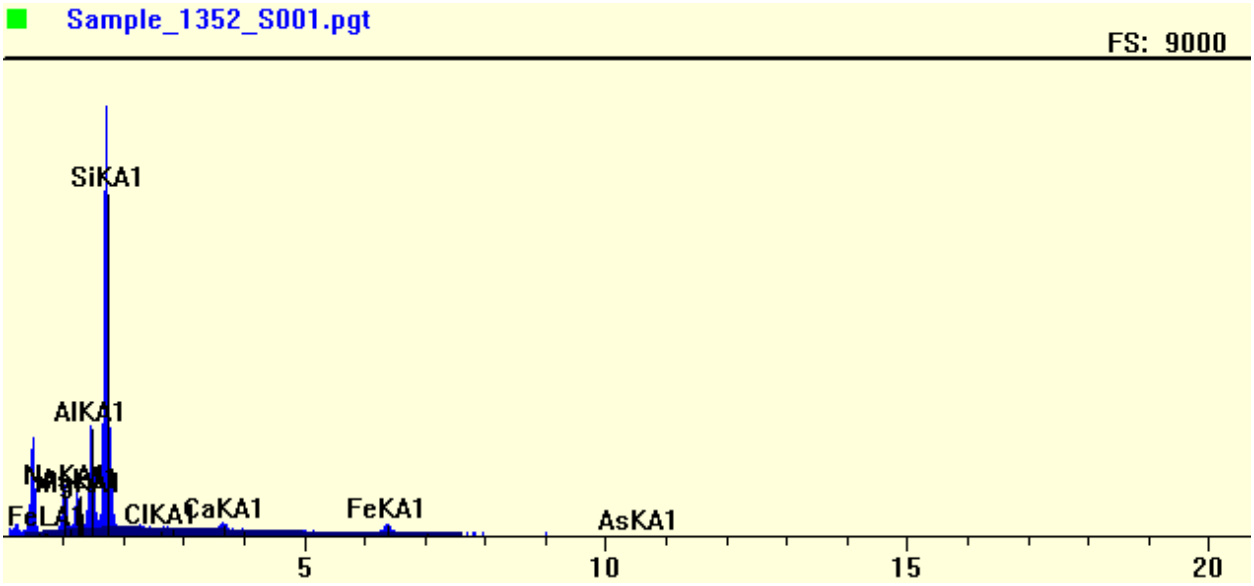


Figure 4.7d.1 Chemical Analysis of Drinking Glass Compact fused at 700^{o}C of area marked X_1

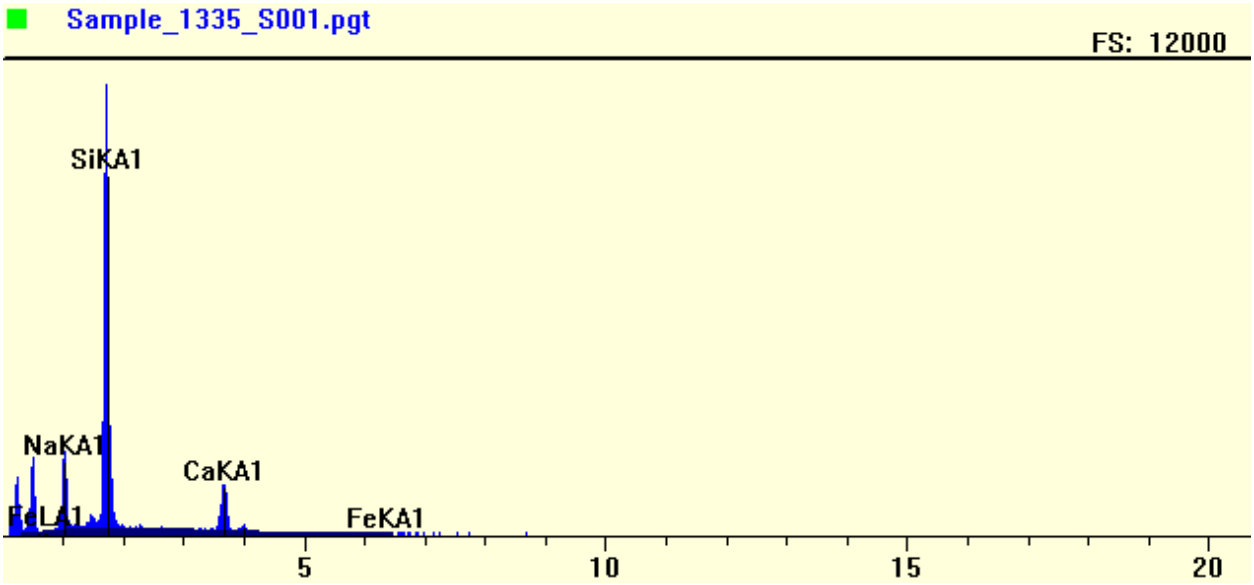


Figure 4.7d.2 Chemical Analysis of Drinking Glass Compact fused at 700^{o}C of area marked X_2

The result of the glass matrix area fused at 700^{o}C in figure 4.7d.2 is comparable to that of the fused particle at 750^{o}C in figure 4.7a.1 indicating that the particle would have been a glass particle. While the result of the particle area marked X_1 in figure 4.7d shown in figure 4.7d.1 may contain bentonite particles.

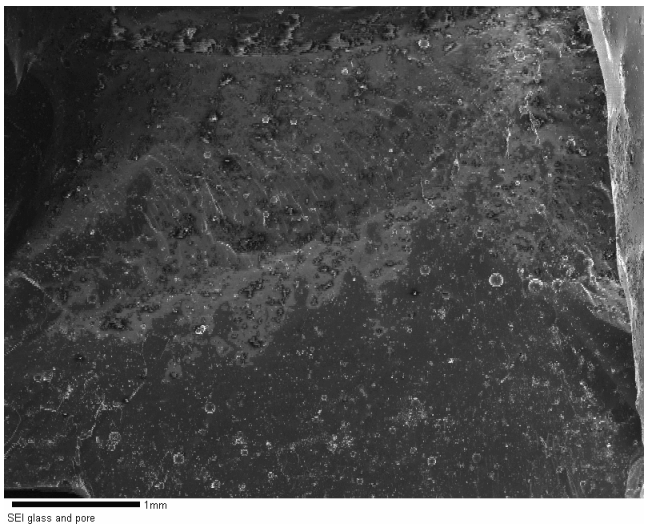


Figure 4.7e Fluorescent tube containing 30% 106 µ, 70% -75 µ and 5% bentonite @ 750^{o}C holding time of 2 hrs

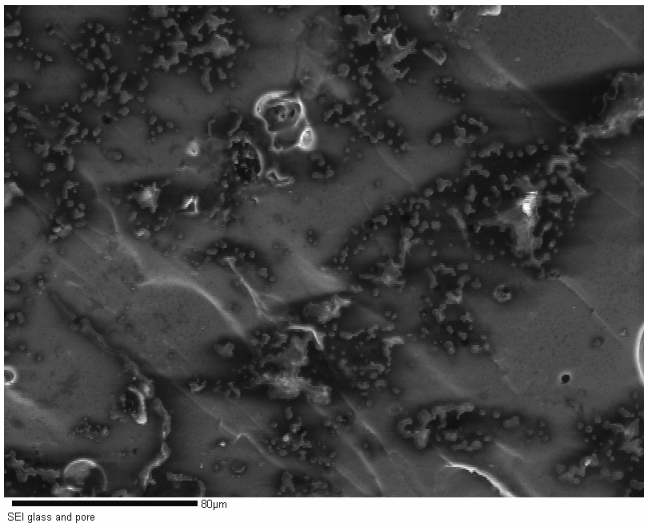


Figure 4.7f Fluorescent tube containing 30% 106µ, 70% -75µ and 5% bentonite @ 750^{o}C holding time of 2 hrs.

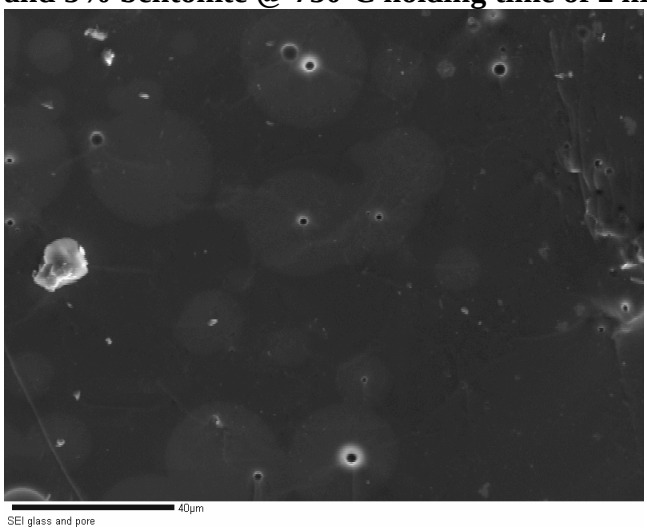


Figure 4.7g Fluorescent tube containing 30% 106µ, 70% -75µ and 5% bentonite @ 750^{o}C with holding time of 2 hrs

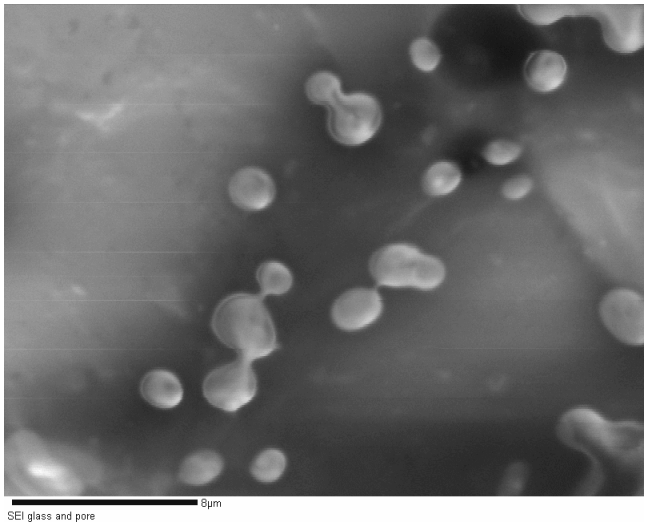


Figure 4.7h Fluorescent tube containing 30% 106µ, 70% -75µ @ 750°C and 5% bentonite holding time of 2 hrs

Figures 4.7.e – 4.7h are different sections of a fracture surface of fluorescent tube fused compact. This fracture surface depicts mainly glass matrix and some pores. Figure 4.7h is has been magnified to show the glass matrix and the type of pores better.

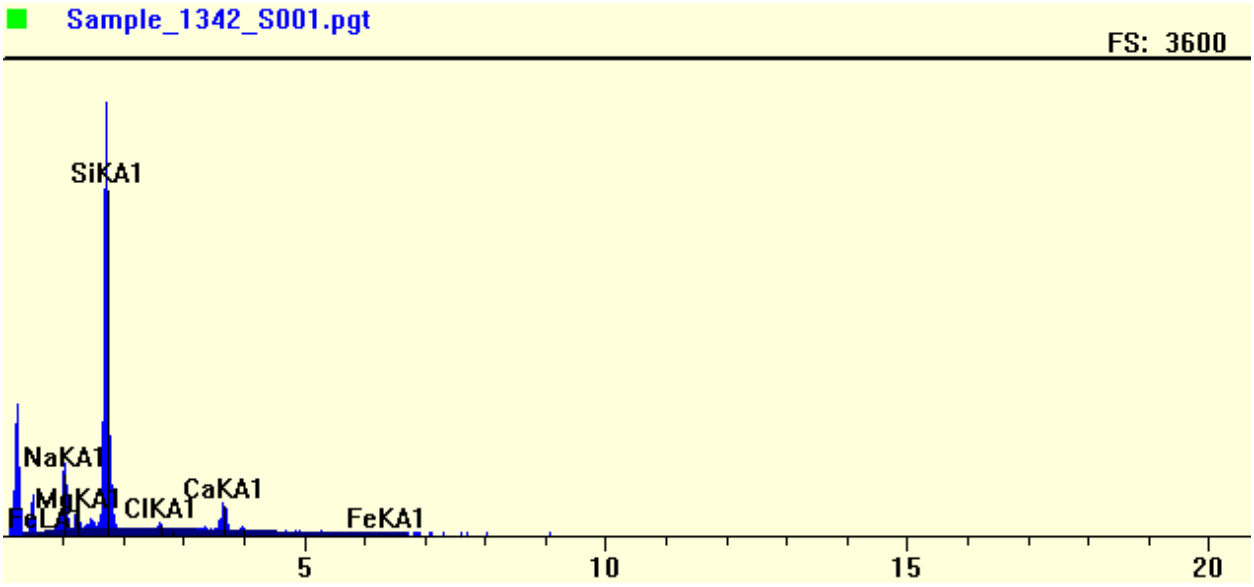


Figure 4.7f.1 Chemical Analysis of Fluorescent tube compact fused at 750°C of the area marked X_3 on figure 4.7f

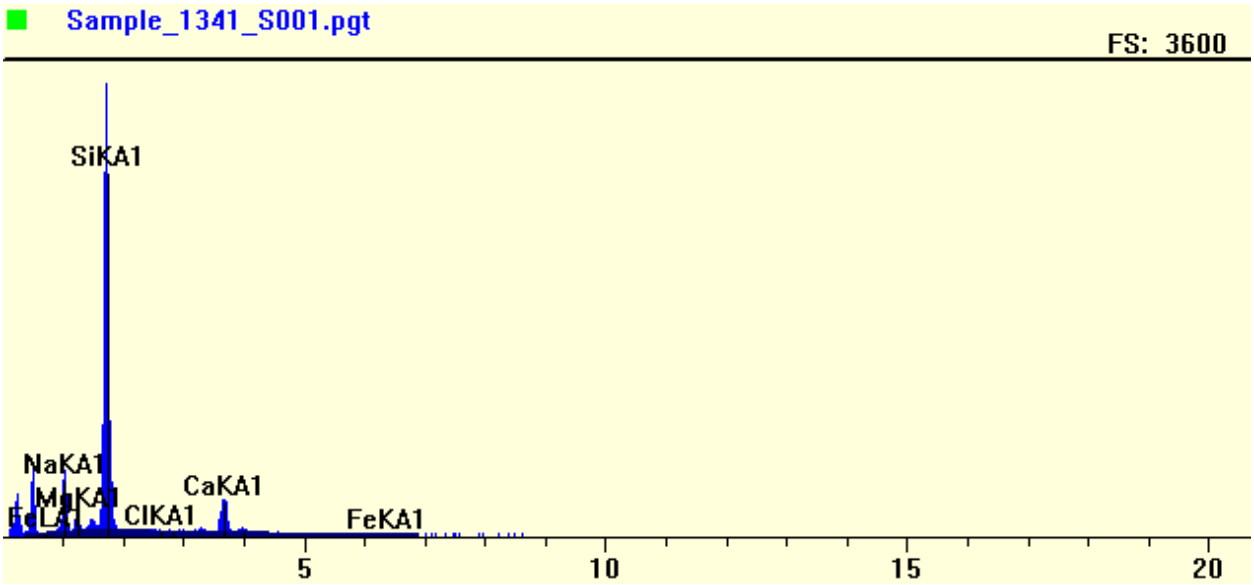


Figure 4.7f.2 Chemical Analysis of Fluorescent tube compact fused at 750°C of the area marked X_4 on figure 4.7f

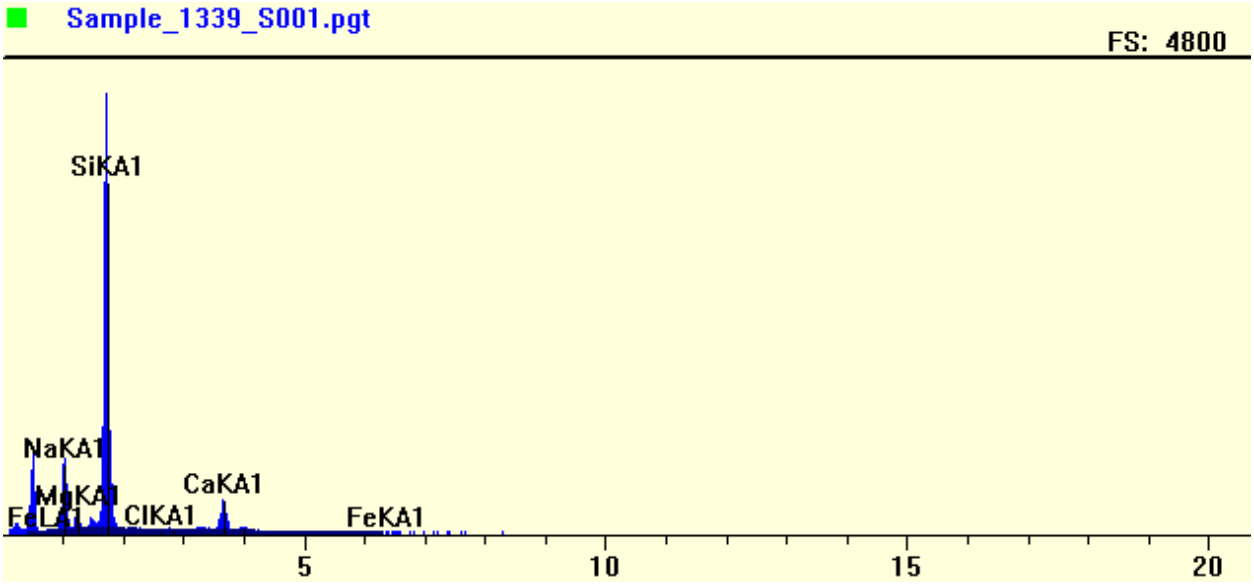


Figure 4.7f.3 Chemical Analysis of Fluorescent tube compact at 750°C of the area marked X_5 on figure 4.7f

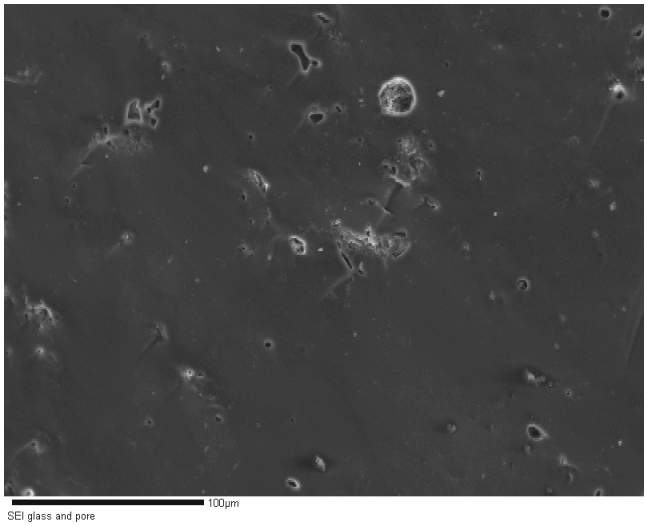


Figure 4.7i Fluorescent tube containing 30% 106µ, 70% -75µ and 5% bentonite @ 700°C holding time of 2 hrs.

Figure 4.7i shows glass matrix and pores, depicting melting of the glass grains and bentonite. It appears however to have more pores than the compact fused at 750°C.

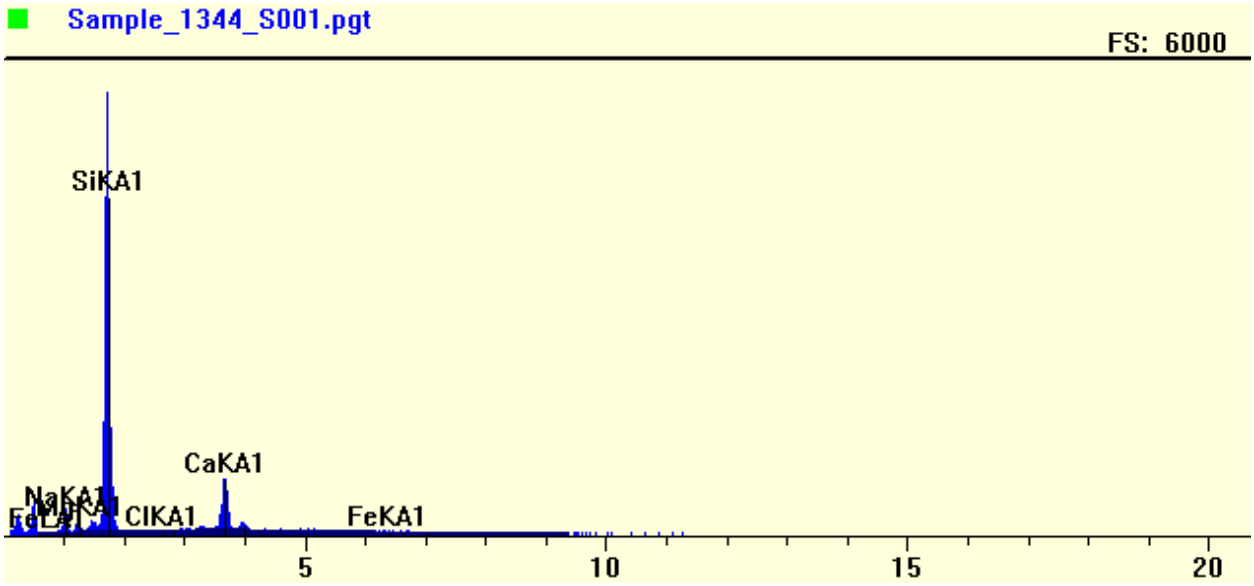


Figure 4.7i.1 Chemical Analysis of Fluorescent tube compact at 700°C of the area marked on X_6 figure 4.7i

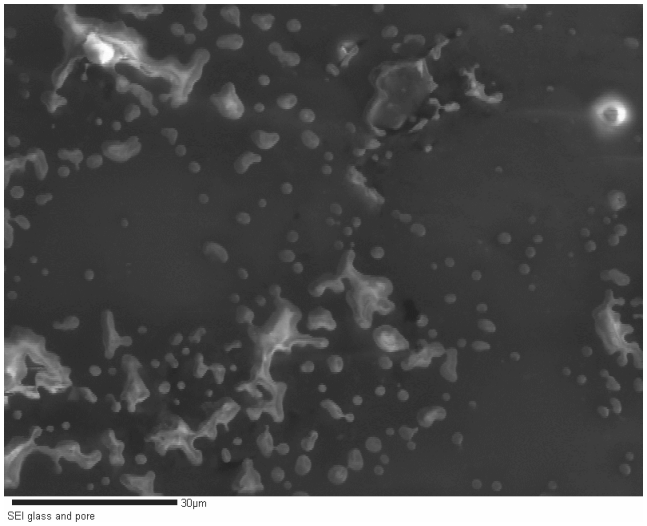


Figure 4.7j Laboratory glass containing 30% 106 µ, 70% -75µ and 5% bentonite @ 750^{o}C holding time of 2 hrs

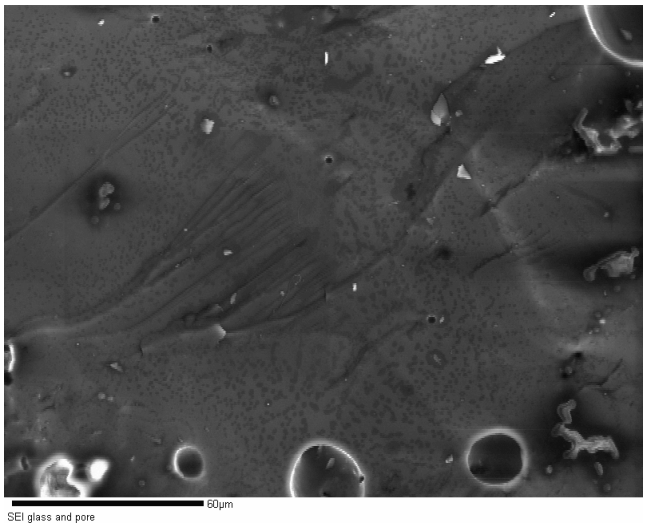


Figure 4.7k Laboratory glass containing 30% 106µ, 70% -75µ and 5% bentonite holding time of 2 hrs

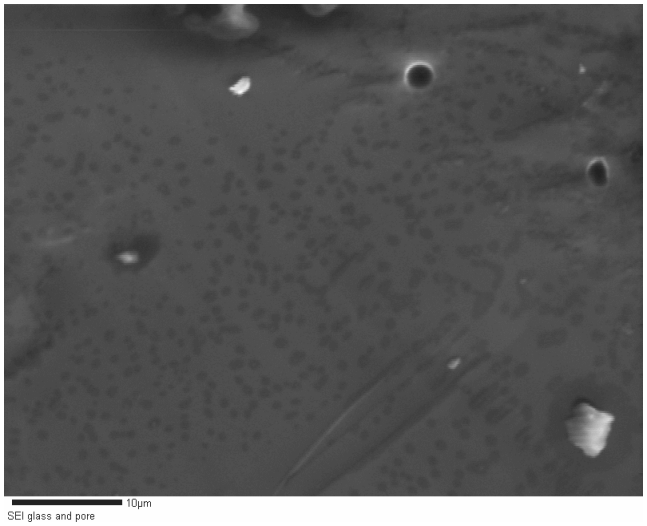


Figure 4.7l Laboratory glass containing 30% 106µ, 70% -75µ and 5% bentonite @ 750°C holding time of 2 hrs

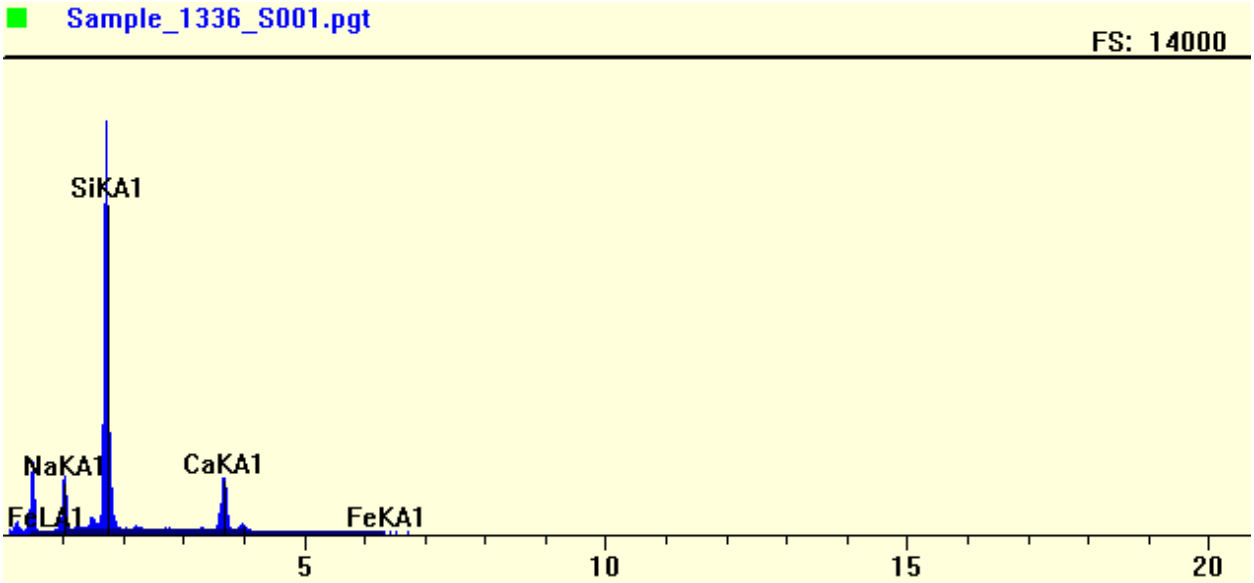


Figure 4.7j.1 Chemical Analysis of Laboratory glass compact fused at 750°C of the area marked on X_7 figure 4.7j

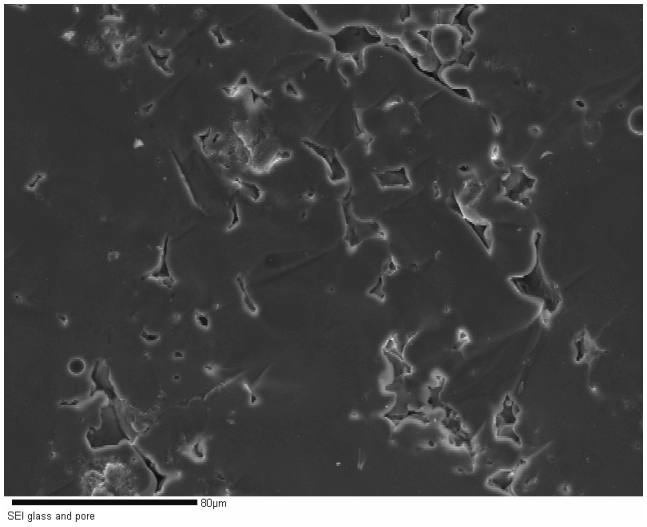


Figure 4.7m Laboratory glass containing 50% 106µ, 50% -75µ and 5% bentonite @ 700^{o}C holding time of 2 hrs

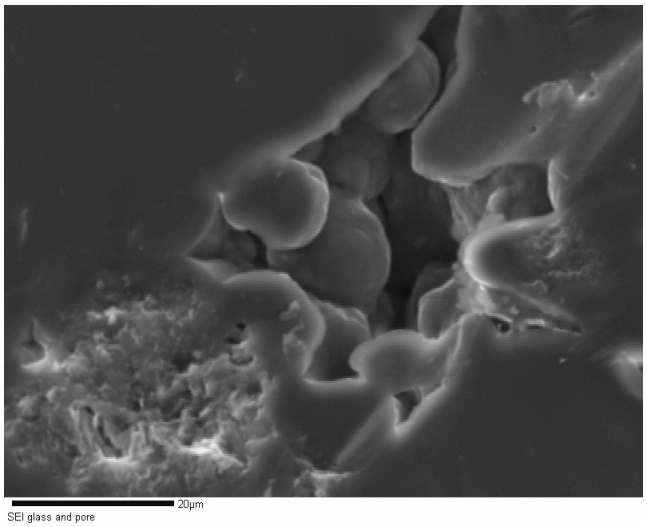


Figure 4.7n Laboratory glass containing 50% 106µ, 50% -75µ and 5% bentonite @ 700^{o}C holding time of 2 hrs

Figure 4.7m shows the microstructure of sintered glass composite from laboratory glass and 5% bentonite at 700^{o}C. This fracture structure show glass matrix and incomplete

fusion of some of the glass particles and as such the pores are irregular in shape. Some bentonite particles are visible. Figure 4.7n is one of the pores enlarged showing some bentonite particles.

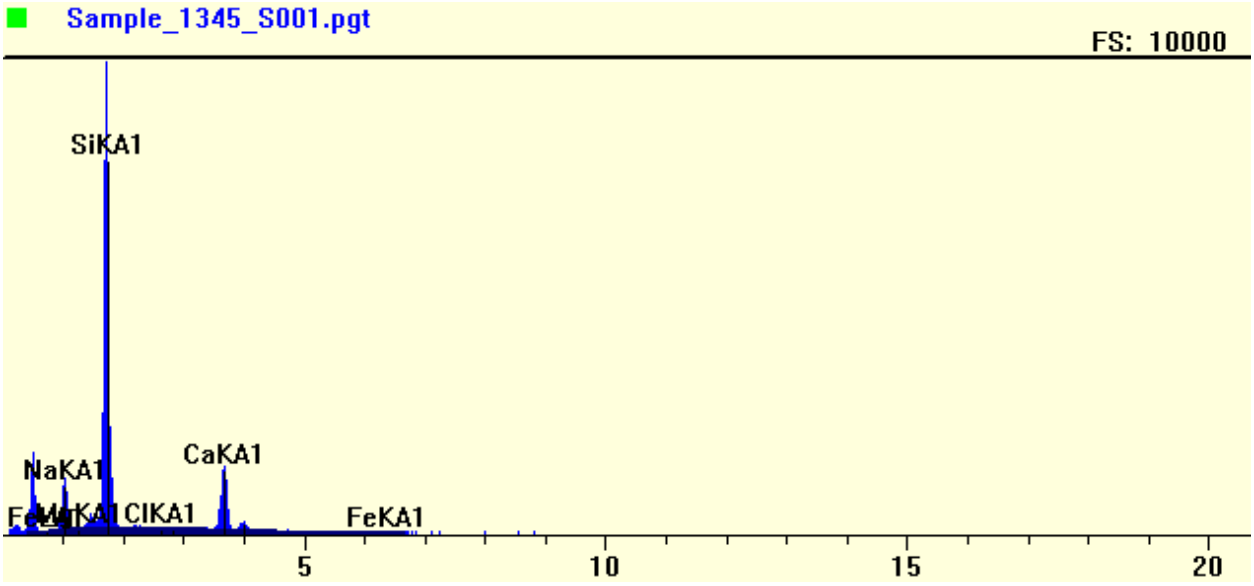


Figure 4.7m.1 Chemical Analysis of Laboratory glass compact fused at 700°C of the matrix area marked on X_8 figure 4.7m

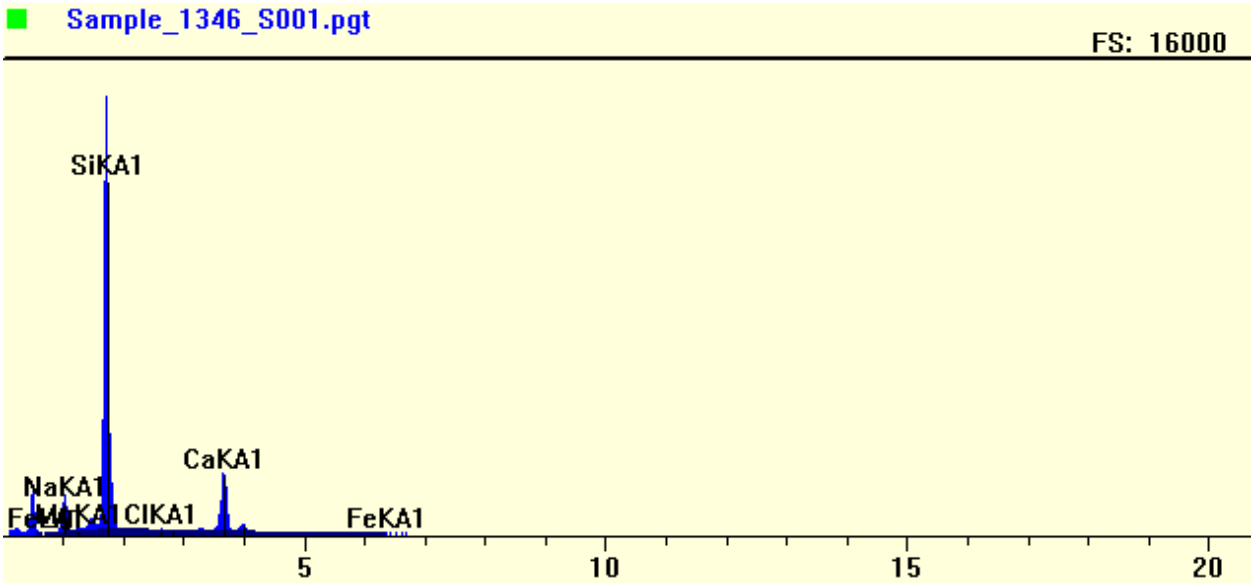


Figure 4.7m.2 Chemical Analysis of Laboratory glass compact fused at 700°C of the area marked on X_9 figure 4.7m (pore particle)

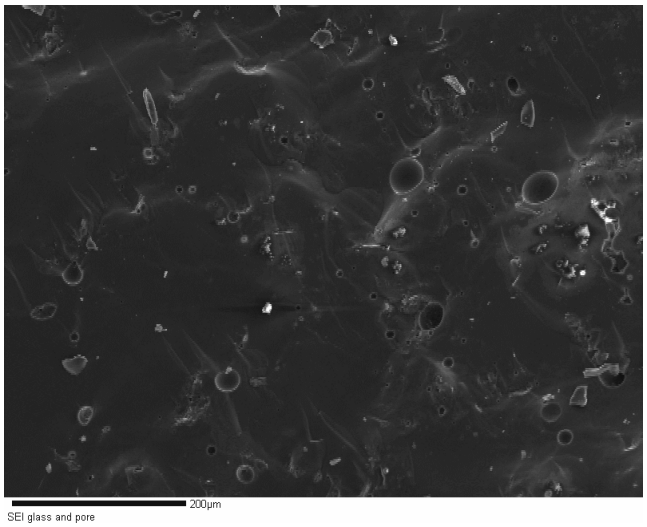


Figure 4.7o Window glass containing 60% 106µ, 40% - 75µ and 5% bentonite @ 750°C holding time of 2 hrs

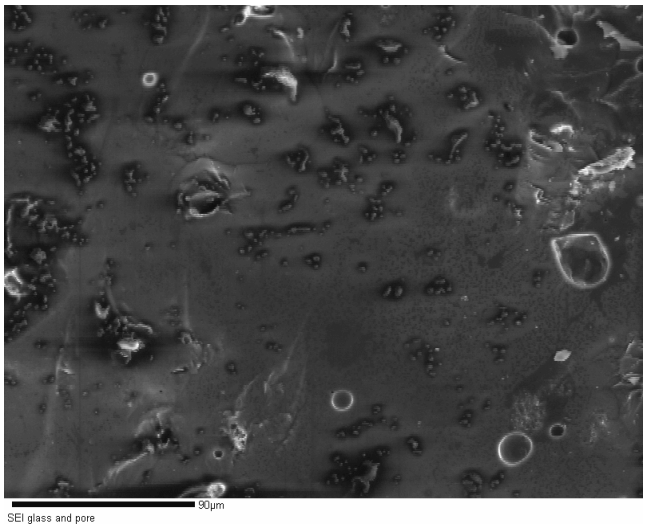


Figure 4.7p Window glass containing 60% 106µ, 40% - 75µ and 5% bentonite @ 750^{o}C holding time of 2 hrs

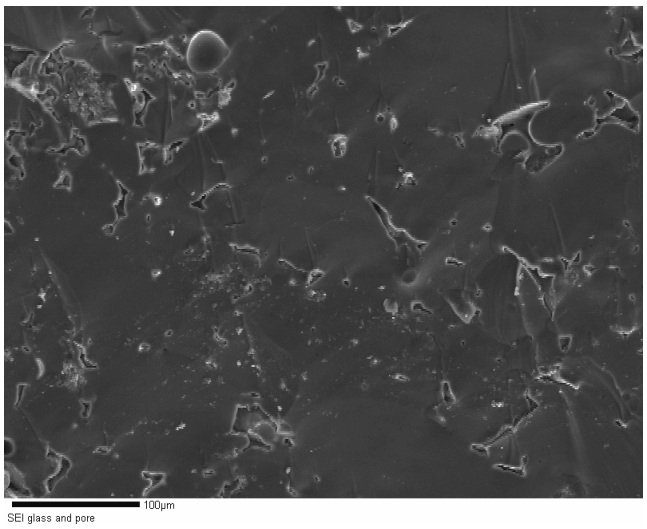


Figure 4.7q Window glass containing 40% 106µ, 60% - 75µ and 5% bentonite @ 700^{o}C holding time of 2 hrs

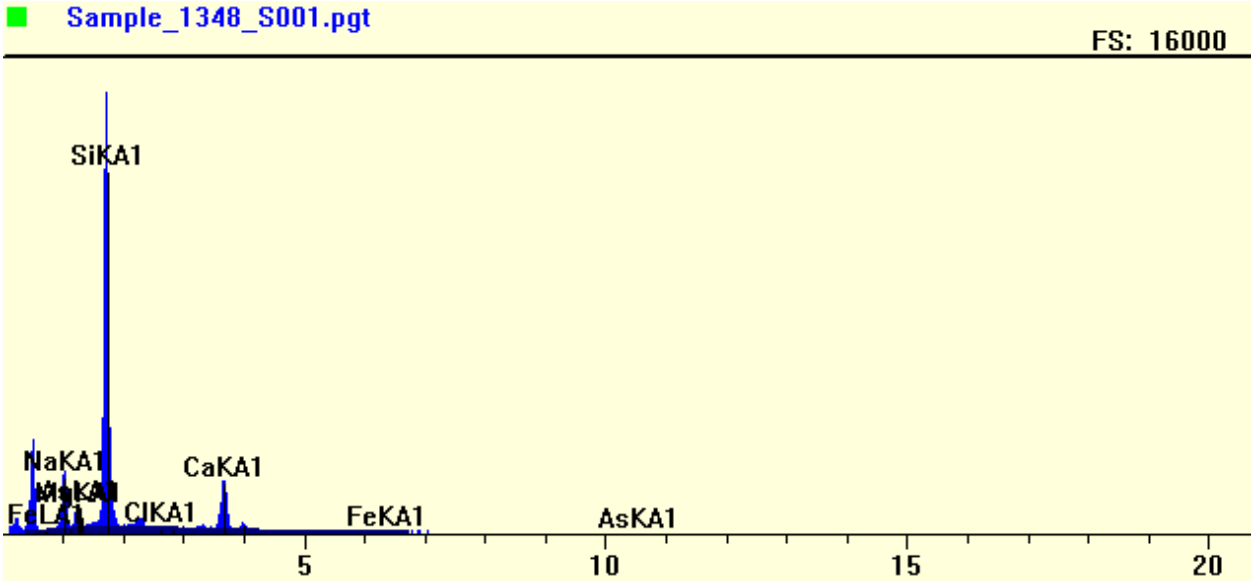


Figure 4.7o.1 Chemical Analysis of Window glass compact fused at 750°C of the particle area marked on X_{10} figure 4.7o

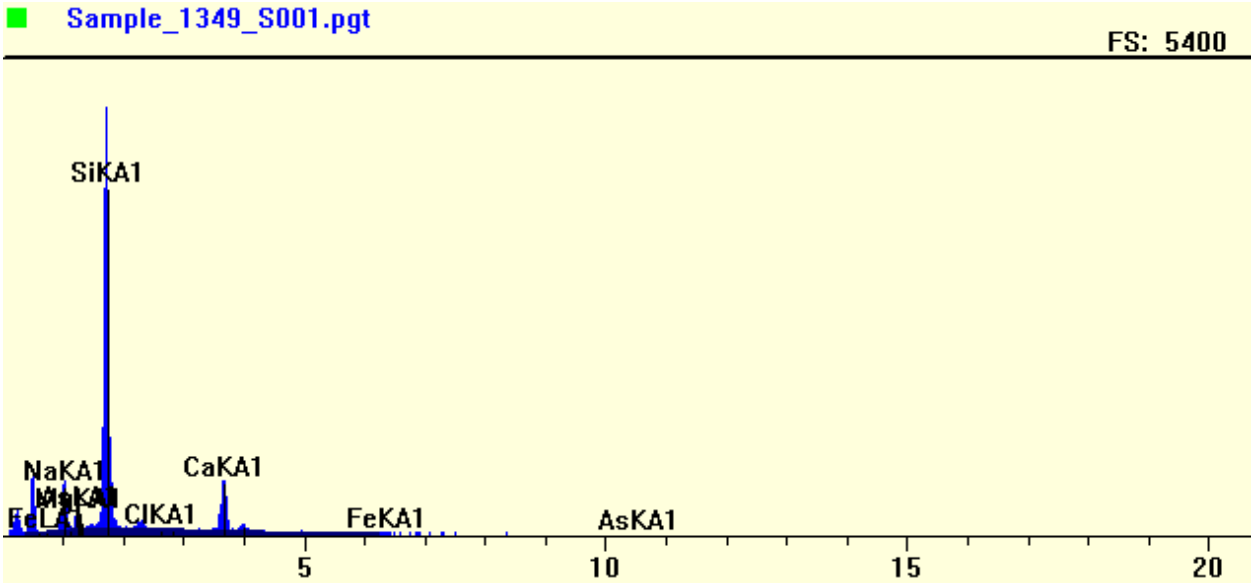


Figure 4.7o.2 Chemical Analysis of Window glass compact fused at 750°C of the matrix area marked on X_{11} figure 4.7o

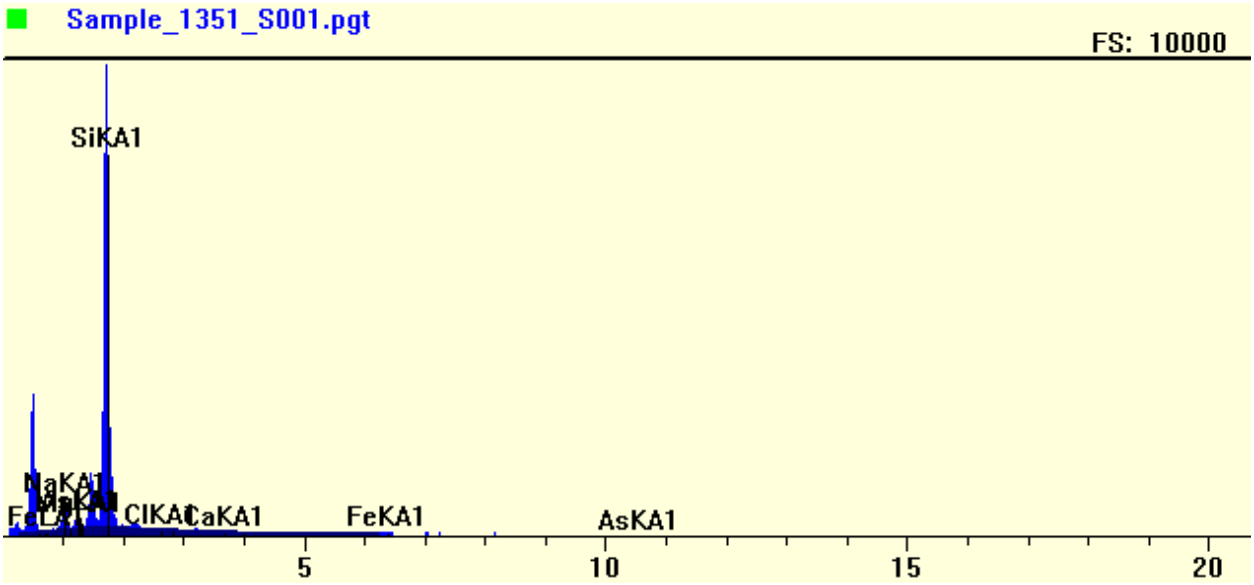


Figure 4.7p.1 Chemical Analysis of Window glass compact fused at 750^{o}C of the matrix area marked on X_{12} figure 4.7p

4.8 Compressive Strength Test

The compressive test was done using the Instron mechanical testing machine. The size of samples for test was required to be in the ratio of 1:2 of diameter: length. It was not possible to produce the size with the available uniaxial press, and as such samples produced were of the ratio 1:1. During the testing single sample was used and then 2 samples together in order to achieve the 1:2 ratio, the results did not show any significant difference as regards the difference in the sizes of the samples (Figures 4.8a – 4.8h).

In this discussion sample d1 is drinking glass test sample of size 1:1 of diameter to length, d2 is size 1:2, f1 is fluorescent tube test sample of size 1:1, f2 is of size 1:2, l1 is laboratory glass test sample of size 1:1, l2 is of size 1:2 and w1 is window glass sample

of size 1:1 and w2 is of size 1:2. Figures 4.8a to 4.8h show the results of the compressive strength of the samples and also tables 4.8a to 4.8h (appendices 15 to 22).

The compressive strength of each of the Samples was calculated using the formula

Compressive strength C = W/A and the results are shown in table 4.8.1

Where C = Compressive strength of specimen lb/in^2 or Kg/cm^2 or Pa.10^4

W = maximum load lbf or Kgf or N indicated by the testing machine

A = average of the gross areas of the gross areas of the upper and lower bearing Surfaces of the specimen in^2 or cm^2

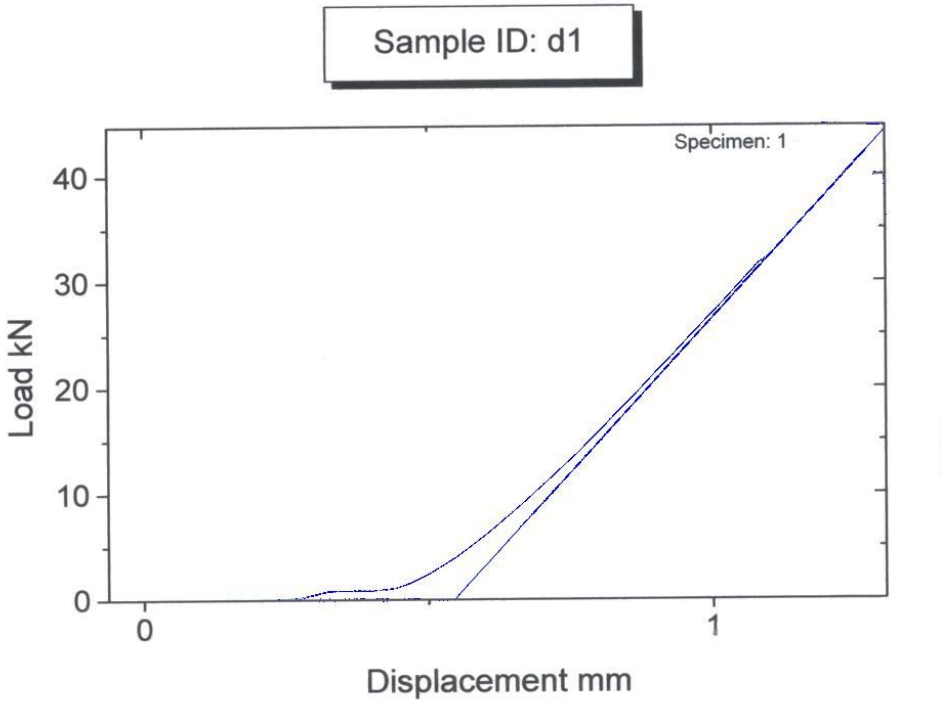


Figure 4.8a Compression of Drinking glass Compacts fused at 700^{o}C of size 1:1

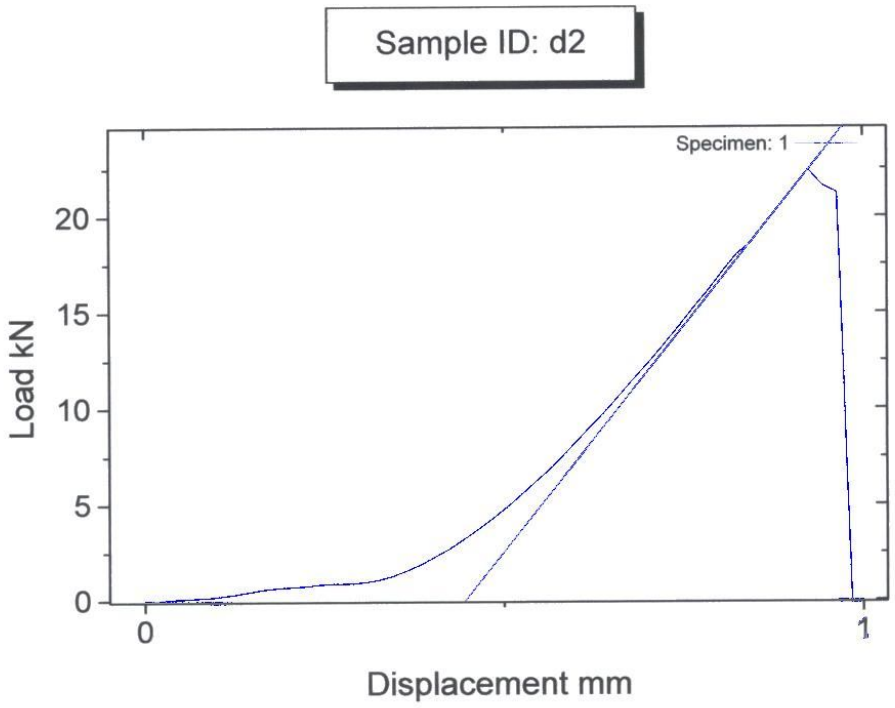


Figure 4.8b Compression of Drinking glass Compacts fused at 700^{o}C of size 1:2

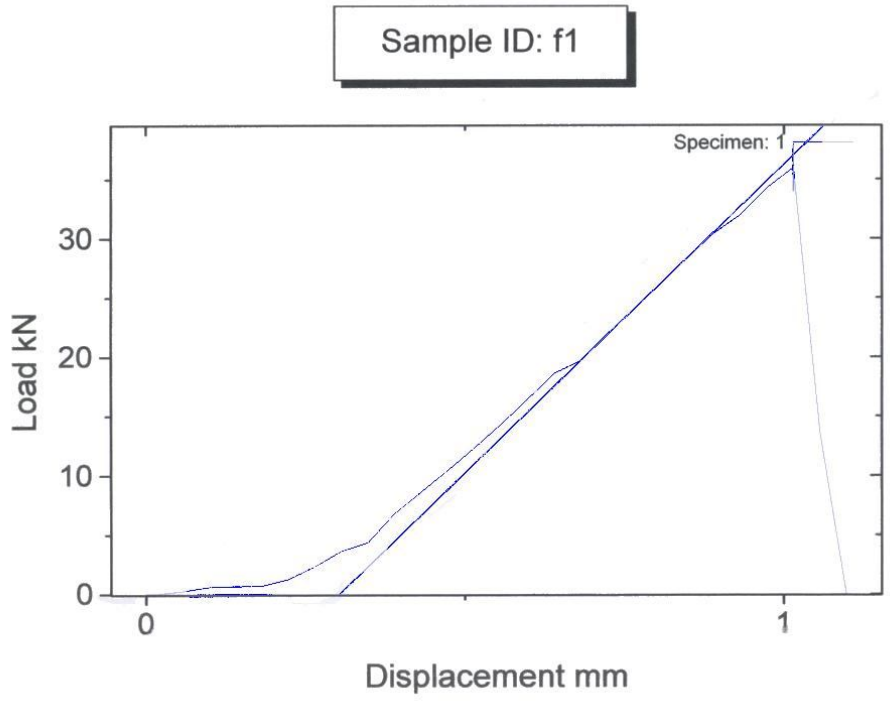


Figure 4.8c Compression of Fluorescent tubes Compacts fused at 700^{o}C of size 1:1

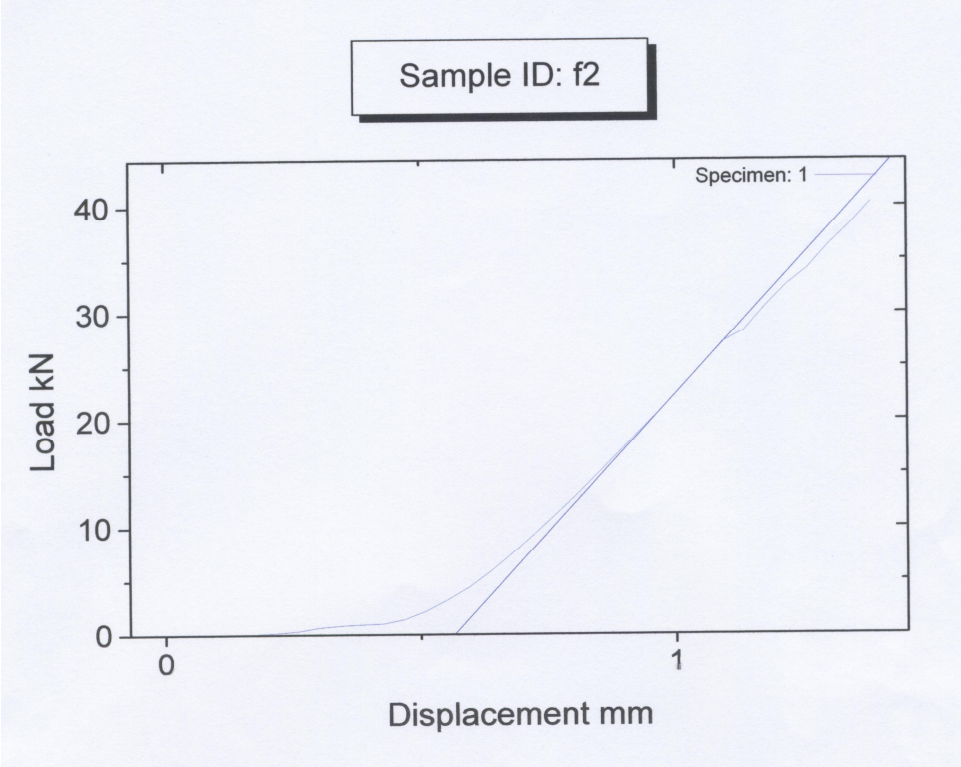


Figure 4.8d Compression of Fluorescent tubes Compacts fused at 700^{o}C of size 1:2

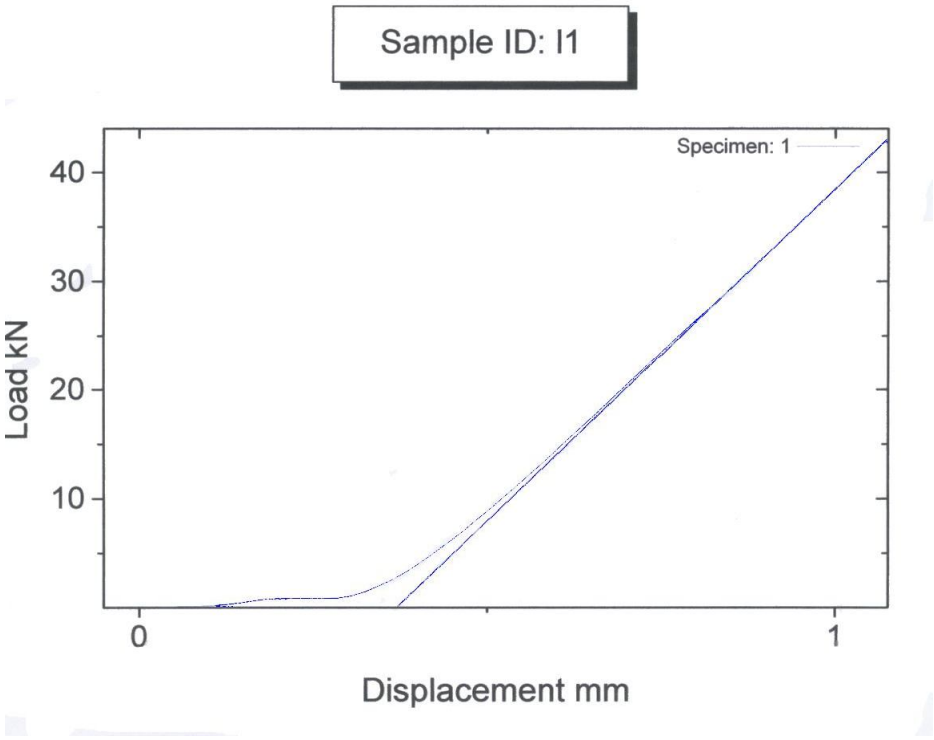


Figure 4.8e Compression of Laboratory glass Compacts fused at 700^{o}C of size 1:1

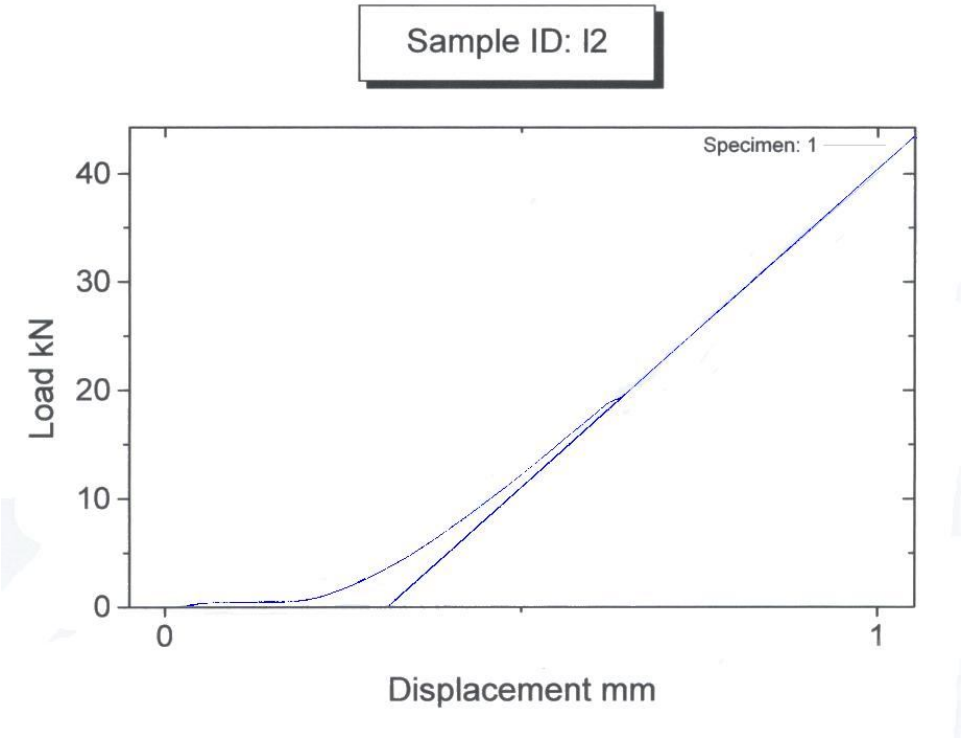


Figure 4.8f Compression of Laboratory glass Compacts fused at 700^{o}C of size 1:2

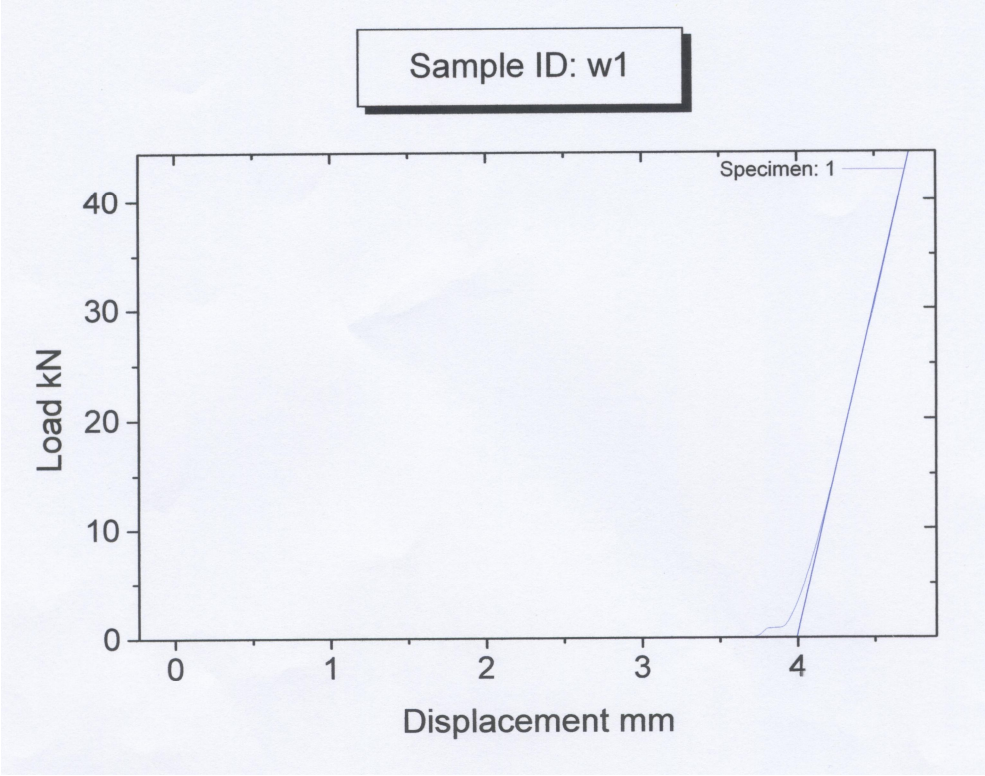


Figure 4.8g Compression of Window glass Compacts fused at 700^{o}C of size 1:1

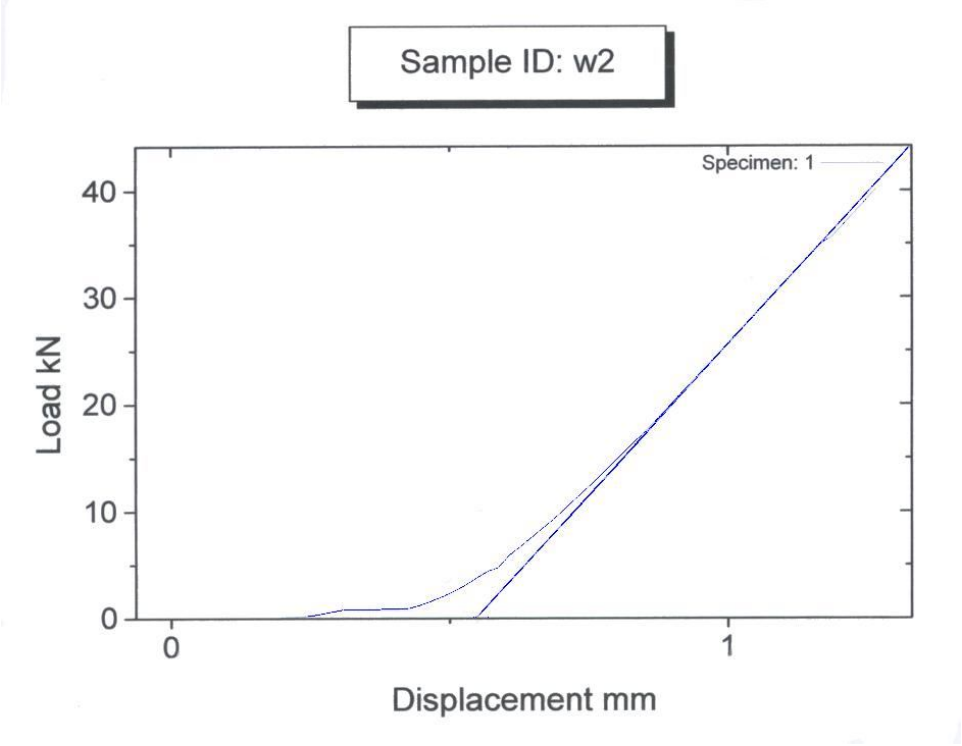


Figure 4.8h Compression of Window glass Compacts fused at 700^{o}C of size 1:2

Table 4.8.1 Compressive Strengths of Compacts fused at 700^{o}C

Sample	Load (KN)	Area (mm^2)	Compressive Strength (MPa)
D1	40.070	660.786	61
D2	22.890	660.786	35
F1	37.090	660.786	56
F2	40.320	660.786	61
L1	40.010	660.786	61
L2	40.250	660.786	61
W1	40.400	660.786	61
W2	40.160	660.786	61

The compressive strength has been presented to the nearest 1.0 MPa and majority of the specimens have the same compressive strength, however compact from drinking glass (D2) having a ratio of length to diameter of 2:1 had a compressive strength of 35 MPa, this perhaps may have arisen from stress built within the specimen. The specimens have come very close to the maximum strength of 69 MPa attainable for its test size (ASTM C 126). It is therefore right to describe these specimens as possessing very good strength to allow their usage as floor tiles.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary and Conclusion

- It has been re-affirmed by this study that tonnes of 'waste glass' lie waste in our environment and if it is not managed it could lead to huge environmental hazard and economic loss. It has also been established that glass is recyclable and the following ways are methods used to recycle these waste glass, the methods include reusing it for its original purpose, altering the principal item to make new products, using it as cullet in the manufacture of new glass, using it as a substitute for a raw material, using it as a raw material in a newly invented product.

- This study exploited the use of waste glasses as substitute for clay in ceramic tile making. Powder compacts (comprising at least 90% recycled glass content) were made using the uniaxial press method. The compacts were sintered and tested using the American Standard Test Methods (ASTM). A good number of the specimens made met the standard specification for ceramic glazed structural clay facing tile, facing brick and solid masonry unit C 126 -99.

- It was possible to produce composites from waste glasses. They can be adopted for the production of floor and wall tiles and the waste glasses can substitute clay. These glass waste utilization will reduce the wastes generation, save cost on production as sintering would occur at a much lower temperature of 700-750^{o}C compared to 1250^{o}C of most clays and also eliminate a separate glazing stage were glazing is required.

5.2 Recommendations

1. Waste glasses (fluorescent tubes, drinking glasses, laboratory glassware and window glasses) should be explored as principal raw materials for tile production.

2. It is recommended that mixed powder compact be made of these glass wastes and tested. This would eliminate sorting if they are to be used for tile production. This recommendation is based on the similarities of their chemical composition and fusion temperatures.

3. The application of colour especially for making glazed tiles should be subjected to further studies.

4. Some of the compacts that were fired to 800^{o}C fused well but expanded due to trapped air. Further studies should be carried out to determine the insulating properties of the compacts and their possible application as insulators.

5. Other forming techniques (slip casting, tape casting) should be experimented upon with the fine recycled glass powder so as to determine their applications.

6. Waste glass from car windscreens and flacconage should be tested for their suitability in tile making. Coloured flacconage for instance might introduce interesting colours to the batch.

7. Small business entrepreneurs should be encouraged to invest in cottage industry that would utilize waste glass as major raw material to save on cost and also create employment, contributing to environmental protection and at the same time influence poverty reduction.

8. Community based organization should be set up to create awareness among the people on the values of recycling waste glass and also to organize the collection of these waste glasses following the Michigan Technological example of recycling day where a day is

set aside periodically to collect recyclable waste materials from the community and the Michigan Waste Management (WM) unit which involves the creation of individual dumpsters for these waste, this effort if established will also create employment for members of the community.

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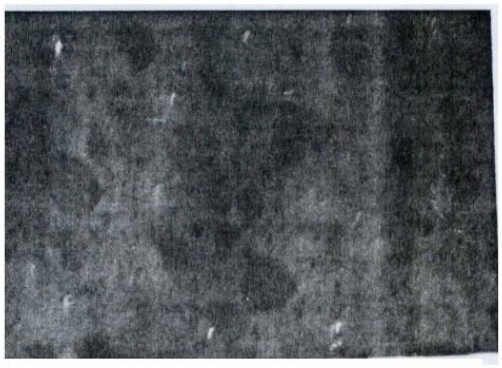
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APPENDICES

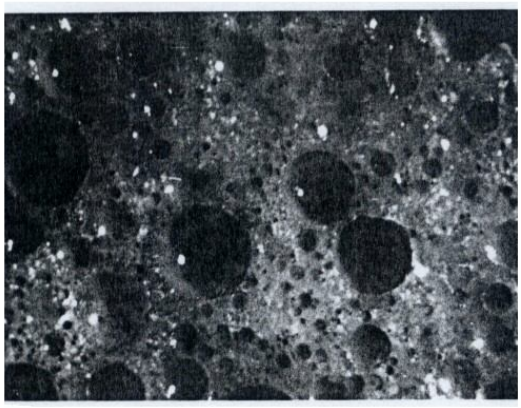
Appendix 1; Micrographs from sintering results of preliminary test



A. Drinking glass compact containing 212µ glass & 15% sodium silicate fused at 720°C with 1 hr holing time



B. Window glass compact containing 212µ glass & 15% sodium silicate fused at 750°C with 2 hrs holing time



C. Fluorescent tube compact containing 425µ glass & 15% sodium silicate fused at 800°C with 3 hrs holing time



D. Laboratory glass compact containing 212µ glass & 15% sodium silicate fused at 900°C with 4 hrs holing time

Appendix 2; Compacts containing Sodium Silicate as Binder



Appendix 3; Firing Shrinkage of Samples fused at 700^{o}C

Table 4.3a Firing Shrinkage of Samples fused at 700°C

Sample	Initial L	Initial D	Dry L	Dry W	L Shrinkage	D Shrinkage	M Shrinkage	Firing L	firing D	L Shrinkage	D Shrikage	M Shrinkage
D 70/30	9	29	9	29	0	0	0	7.5	26.5	1.5	2.5	2
D 60/40	9	29	9	29	0	0	0	8	26.5	1	2.5	1.75
D 50/50	9	29	9	29	0	0	0	8	26	1	3	2
D 40/60	9	29	9	29	0	0	0	8	26	1	3	2
D 30/70	9	29	9	29	0	0	0	8	26	1	3	2
F 70/30	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
F 60/40	9	29	9	29	0	0	0	7.5	25.5	1.5	3.5	2.25
F 50/50	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
F 40/60	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
F 30/70	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
L 70/30	9	29	8	29	1	0	0.5	7.5	26.5	0.5/1.5	2.5	2
L 60/40	9	29	8	29	1	0	0.5	7.5	26	0.5/1.5	3	2.25
L 50/50	9	29	8.5	29	0.5	0	0.25	8	26	0.5/1.5	3	2
L 40/60	9	29	9	29	0	0	0	8	26	1	3	2
L 30/70	9	29	9	29	0	0	0	8	26	1	3	2
W 70/30	9	29	8	29	1	0	0.5	7.5	26	0.5/1.5	3	2.25
W 60/40	9	29	8	29	1	0	0.5	7.5	26	0.5/1.5	3	2.25
W 50/50	9	29	8.5	29	0.5	0	0.25	8	26	0.5/1	3	2
W 40/60	9	29	8.5	29	0.5	0	0.25	8	25.5	0.5/1	3.5	2.25
W 30/70	9	29	8.5	29	0.5	0	0.25	8	25.5	0.5/1	3.5	2.25

Appendix 4; Firing Shrinkage of samples fused at 725°C

Table 4.3b Firing Shrinkage of Samples fused at 725°C

Sample	Initial L	Initial D	Dry L	Dry W	L Shrinkage	D Shrinkage	M Shrinkage	Firing L	firing D	L Shrinkage	D Shrikage	M Shrinkage
D 70/30	9	29	9	29	0	0	0	7.5	26	1.5	3	2.25
D 60/40	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
D 50/50	9	29	9	29	0	0	0	7.5	25.5	1.5	3.5	2.5
D 40/60	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
D 30/70	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
F 70/30	9	29	9	29	0	0	0	7.5	25	1.5	4	2.75
F 60/40	9	29	9	29	0	0	0	7.5	25	1.5	4	2.75
F 50/50	9	29	9	29	0	0	0	7.5	25	1.5	4	2.75
F 40/60	9	29	9	29	0	0	0	7.5	25	1.5	4	2.75
F 30/70	9	29	9	29	0	0	0	7.5	25	1.5	4	2.75
L 70/30	9	29	8	29	1	0	0.5	7.5	26	1.5	3	2.25
L 60/40	9	29	8	29	1	0	0.5	7.5	26	1.5	3	2.25
L 50/50	9	29	8.5	29	0.5	0	0.25	7.5	26	1.5	3	2.25
L 40/60	9	29	9	29	0	0	0	7.5	26	1.5	3	2.25
L 30/70	9	29	9	29	0	0	0	8	26	1	3	2
W 70/30	9	29	8	29	1	0	0.5	7.5	26	1.5	3	2.25
W 60/40	9	29	8	29	1	0	0.5	7.5	25.5	1.5	3.5	2.5
W 50/50	9	29	8.5	29	0.5	0	0.25	7.5	25.5	1.5	3.5	2.5
W 40/60	9	29	8.5	29	0.5	0	0.25	8	25.5	1	3.5	2.25
W 30/70	9	29	8.5	29	0.5	0	0.25	8	25.5	1	3.5	2.25

Appendix 5; Firing Shrinkage of samples fused at 750°C

Table 4.3c Firing Shrinkage of Samples fused at 750°C

Sample	Initial L	Initial D	Dry L	Dry W	L Shrinkage	D Shrinkage	M Shrinkage	Firing L	firing D	L Shrinkage	D Shrikage	M Shrinkage
D 70/30	9	29	9	29	0	0	0	7	26	2	3	2.5
D 60/40	9	29	9	29	0	0	0	7	25.5	2	3.5	2.75
D 50/50	9	29	9	29	0	0	0	7	25.5	2	3.5	2.75
D 40/60	9	29	9	29	0	0	0	7.5	25.5	1.5	3.5	2.5
D 30/70	9	29	9	29	0	0	0	8	25.5	1	3.5	2.25
F 70/30	9	29	9	29	0	0	0	7	26	2	3	2.5
F 60/40	9	29	9	29	0	0	0	7	26	2	3	2.5
F 50/50	9	29	9	29	0	0	0	7	26	2	3	2.5
F 40/60	9	29	9	29	0	0	0	7	26	2	3	2.5
F 30/70	9	29	9	29	0	0	0	7.5	25.5	1.5	3.5	2.5
L 70/30	9	29	8	29	1	0	0.5	7.5	25.5	1.5	3.5	2.5
L 60/40	9	29	8	29	1	0	0.5	7.5	25.5	1.5	3.5	2.5
L 50/50	9	29	8.5	29	0.5	0	0.25	7.5	25.5	1.5	3.5	2.5
L 40/60	9	29	9	29	0	0	0	7.5	25.5	1.5	3.5	2.5
L 30/70	9	29	9	29	0	0	0	7.5	25.5	1.5	3.5	2.5
W 70/30	9	29	8	29	1	0	0.5	7.5	26	1.5	3	2.25
W 60/40	9	29	8	29	1	0	0.5	7.5	26	1.5	3	2.25
W 50/50	9	29	8.5	29	0.5	0	0.25	7.5	25.5	1.5	3.5	2.5
W 40/60	9	29	8.5	29	0.5	0	0.25	7.5	25.5	1.5	3.5	2.5
W 30/70	9	29	8.5	29	0.5	0	0.25	7.5	25.5	1.5	3.5	2.5

Appendix 6; 5 hr and 24 hr absorption test for samples fused at 700°C

Table 4.5a 5hr and 24 hr absorption test for samples fused at 700oC

Sample	wt @ 700oC	5hr absorp	absortion	% absortion	24hr absorp	absortion	% absortion
D 70/30	9.482	9.694	0.212	2.239	9.696	0.214	2.257
D 60/40	9.544	9.709	0.165	1.729	9.711	0.167	1.75
D 50/50	9.551	9.693	0.142	1.487	9.696	0.147	1.539
D 40/60	9.533	9.684	0.151	1.584	9.693	0.16	1.678
D 30/70	9.532	9.777	0.245	2.57	9.785	0.253	2.654
F 70/30	9.523	9.526	0.003	0.032	9.529	0.006	0.063
F 60/40	9.473	9.474	0.001	0.011	9.476	0.003	0.031
F 50/50	9.604	9.604	0	0	9.606	0.002	0.021
F 40/60	9.574	9.574	0	0	9.574	0	0
F 30/70	9.555	9.556	0.001	0.01	9.556	0.001	0.01
L 70/30	9.513	9.634	0.121	1.272	9.635	0.122	1.282
L 60/40	9.548	9.636	0.088	0.922	9.64	0.092	0.964
L 50/50	9.584	9.669	0.085	0.887	9.672	0.088	0.918
L 40/60	9.595	9.7	0.115	1.199	9.704	0.109	1.136
L 30/70	9.64	9.917	0.257	2.666	9.925	0.285	2.956
W 70/30	9.556	9.662	0.106	1.109	9.663	0.107	1.12
W 60/40	9.634	9.753	0.119	1.235	9.76	0.126	1.308
W 50/50	9.682	9.817	0.135	1.394	9.825	0.143	1.477
W 40/60	9.666	9.708	0.042	0.435	9.711	0.045	0.466
W 30/70	9.552	9.76	0.208	2.118	9.766	0.214	2.24

Appendix 7; 5 hr and 24 hr absorption test for samples fused at 725°C

Table 4.5b 5hr and 24 hr absorption test for samples fused at 725°C

Sample	wt @ 725oC	5hr absorp	absortion	% absortion	24hr absorp	absortion	% absortion
D 70/30	9.489	9.5	0.011	0.116	9.5	0.011	0.116
D 60/40	9.598	9.599	0.001	0.01	9.599	0.001	0.01
D 50/50	9.572	9.574	0.002	0.021	9.574	0.002	0.021
D 40/60	9.522	9.523	0.001	0.011	9.523	0.001	0.011
D 30/70	9.571	9.589	0.018	0.188	9.592	0.021	0.219
F 70/30	9.564	9.564	0	0	9.564	0	0
F 60/40	9.491	9.491	0	0	9.491	0	0
F 50/50	9.606	9.606	0	0	9.606	0	0
F 40/60	9.553	9.553	0	0	9.553	0	0
F 30/70	9.602	9.602	0	0	9.602	0	0
L 70/30	9.506	9.508	0.002	0.021	9.508	0.002	0.021
L 60/40	9.562	9.563	0.001	0.01	9.563	0.001	0.01
L 50/50	9.661	9.664	0.003	0.031	9.664	0.003	0.031
L 40/60	9.584	9.586	0.002	0.021	9.586	0.002	0.021
L 30/70	9.584	9.612	0.028	0.292	9.615	0.031	0.323
W 70/30	9.52	9.521	0.001	0.011	9.521	0.001	0.011
W 60/40	9.6	9.601	0.001	0.01	9.601	0.001	0.01
W 50/50	9.711	9.724	0.013	0.134	9.724	0.013	0.134
W 40/60	9.642	9.643	0.001	0.01	9.643	0.001	0.01

Appendix 8; 5 hr and 24 hr absorption test for samples fused at 750°C

Table 4.5c 5hr and 24 hr absorption test for samples fused at 750°C

Sample	wt @ 750oC	5hr absorp	absortion	% absortion	24hr absorp	absortion	% absortion
D 70/30	9.484	9.484	0	0	9.484	0	0
D 60/40	9.578	9.578	0	0	9.578	0	0
D 50/50	9.563	9.563	0	0	9.563	0	0
D 40/60	9.548	9.548	0	0	9.548	0	0
D 30/70	9.553	9.553	0	0	9.553	0	0
F 70/30	9.558	9.558	0	0	9.558	0	0
F 60/40	9.509	9.509	0	0	9.509	0	0
F 50/50	9.59	9.59	0	0	9.59	0	0
F 40/60	9.515	9.515	0	0	9.515	0	0
F 30/70	9.587	9.587	0	0	9.587	0	0
L 70/30	9.52	9.52	0	0	9.52	0	0
L 60/40	9.565	9.565	0	0	9.565	0	0
L 50/50	9.62	9.62	0	0	9.62	0	0
L 40/60	9.605	9.605	0	0	9.605	0	0
L 30/70	9.625	9.625	0	0	9.625	0	0
W 70/30	9.523	9.523	0	0	9.523	0	0
W 60/40	9.657	9.657	0	0	9.657	0	0
W 50/50	9.699	9.694	0	0	9.699	0	0
W 40/60	9.628	9.628	0	0	9.628	0	0
W 30/70	9.544	9.546	0.002	0.021	9.546	0.002	0.021

Appendix 9; 1 hr, 2 hrs and 5 hrs boiling test for samples fused at 700°C

Table 4.5d 5hr and 24 hr 1 hr, 2 hrs and 5 hrs boiling test for samples fused at 700°C

Sample	wt @ 700oC	1hr boiling	absortion	% absortion	2hr boiling	absortion	% absortion	5hr boiling	absortion	% absortion
D 70/30	9.482	9.853	0.371	3.912	9.866	0.384	4.05	9.896	0.414	4.366
D 60/40	9.544	9.867	0.323	3.384	9.876	0.332	3.479	9.882	0.338	3.541
D 50/50	9.551	9.781	0.23	2.408	9.79	0.239	2.502	9.795	0.244	2.555
D 40/60	9.533	9.795	0.262	2.748	9.805	0.272	2.853	9.805	0.272	2.853
D 30/70	9.532	9.897	0.365	3.829	9.914	0.382	4.008	9.925	0.393	4.123
F 70/30	9.523	9.529	0.006	0.063	9.529	0.006	0.063	9.532	0.009	0.095
F 60/40	9.473	9.476	0.003	0.032	9.476	0.003	0.032	9.477	0.004	0.042
F 50/50	9.604	9.606	0.002	0.021	9.606	0.002	0.021	9.608	0.004	0.042
F 40/60	9.574	9.575	0.001	0.01	9.575	0.001	0.01	9.578	0.004	0.042
F 30/70	9.555	9.556	0.001	0.01	9.556	0.001	0.01	9.557	0.002	0.021
L 70/30	9.513	9.743	0.23	2.418	9.752	0.239	2.512	9.754	0.241	2.533
L 60/40	9.548	9.684	0.136	1.424	9.689	0.141	1.476	9.701	0.153	1.602
L 50/50	9.584	9.694	0.11	1.148	9.702	0.118	1.231	9.706	0.122	1.273
L 40/60	9.595	9.727	0.132	1.376	9.737	0.142	1.48	9.742	0.147	1.532
L 30/70	9.64	10.04	0.4	4.149	10.057	0.417	4.343	10.071	0.431	4.471
W 70/30	9.556	9.734	0.178	1.862	9.756	0.2	2.093	9.763	0.207	2.166
W 60/40	9.634	9.81	0.176	1.827	9.828	0.194	2.014	9.832	0.198	2.055
W 50/50	9.682	9.872	0.19	1.962	9.881	0.199	2.055	9.889	0.207	2.138
W 40/60	9.666	9.726	0.06	0.621	9.73	0.064	0.662	9.732	0.066	0.683
W 30/70	9.552	9.836	0.284	2.973	9.853	0.301	3.151	9.857	0.305	3.193

Appendix 10; 1 hr, 2 hrs and 5 hrs boiling test for samples fused at 725°C

Table 4.5e 5hr and 24 hr 1 hr, 2 hrs and 5 hrs boiling test for samples fused at 725°C

Sample	wt @ 725oC	1hr boiling	absortion	% absortion	2hr boiling	absortion	% absortion	5hr boiling	absortion	% absortion
D 70/30	9.489	9.503	0.014	0.148	9.504	0.015	0.158	9.506	0.017	0.179
D 60/40	9.598	9.6	0.002	0.021	9.601	0.003	0.031	9.602	0.004	0.42
D 50/50	9.572	9.574	0.002	0.021	9.576	0.004	0.042	9.577	0.003	0.031
D 40/60	9.522	9.523	0.001	0.011	9.526	0.004	0.042	9.528	0.001	0.011
D 30/70	9.571	9.597	0.028	0.292	9.599	0.028	0.292	9.599	0.028	0.293
F 70/30	9.564	9.564	0	0	9.564	0	0	9.564	0	0
F 60/40	9.491	9.491	0	0	9.491	0	0	9.491	0	0
F 50/50	9.606	9.606	0	0	9.606	0	0	9.606	0	0
F 40/60	9.553	9.553	0	0	553	0	0	9.553	0	0
F 30/70	9.602	9.602	0	0	9.602	0	0	9.602	0	0
L 70/30	9.506	9.508	0.002	0.021	9.508	0.002	0.021	9.508	0.002	0.021
L 60/40	9.562	9.563	0.001	0.01	9.563	0.001	0.01	9.563	0.001	0.01
L 50/50	9.661	9.664	0.003	0.031	9.664	0.003	0.031	9.664	0.003	0.031
L 40/60	9.584	9.586	0.002	0.021	9.586	0.002	0.021	9.586	0.002	0.021
L 30/70	9.584	9.62	0.036	0.376	9.624	0.04	0.417	9.625	0.041	0.428
W 70/30	9.52	9.522	0.002	0.021	9.522	0.002	0.021	9.522	0.002	0.021
W 60/40	9.6	9.601	0.001	0.01	9.602	0.002	0.021	9.604	0.004	0.042
W 50/50	9.711	9.728	0.017	0.175	9.731	0.02	0.206	9.732	0.021	0.216
W 40/60	9.642	9.645	0.003	0.031	9.645	0.003	0.311	9.646	0.004	0.41
W 30/70	9.598	9.634	0.036	0.375	9.639	0.041	0.427	9.64	0.042	0.438

Appendix 11; 1 hr, 2 hrs and 5 hrs boiling test for samples fused at 750° C

Table 4.5f 5hr and 24 hr 1 hr, 2 hrs and 5 hrs boiling test for samples fused at 750°C

Sample	wt @ 750oC	1hr boiling	absortion	% absortion	2hr boiling	absortion	% absortion	5hr boiling	absortion	% absortion
D 70/30	9.484	9.484	0	0	9.484	0	0	9.484	0	0
D 60/40	9.578	9.578	0	0	9.578	0	0	9.578	0	0
D 50/50	9.563	9.563	0	0	9.563	0	0	9.563	0	0
D 40/60	9.548	9.548	0	0	9.548	0	0	9.548	0	0
D 30/70	9.553	9.553	0	0	9.553	0	0	9.553	0	0
F 70/30	9.558	9.558	0	0	9.558	0	0	9.558	0	0
F 60/40	9.509	9.509	0	0	9.509	0	0	9.509	0	0
F 50/50	9.59	9.59	0	0	9.59	0	0	9.59	0	0
F 40/60	9.515	0.515	0	0	9.515	0	0	9.515	0	0
F 30/70	9.587	9.587	0	0	9.587	0	0	9.587	0	0
L 70/30	9.52	9.52	0	0	9.52	0	0	9.52	0	0
L 60/40	9.565	9.565	0	0	10	0	0	9.565	0	0
L 50/50	9.62	9.62	0	0	9.62	0	0	9.62	0	0
L 40/60	9.605	9.605	0	0	9.605	0	0	9.605	0	0
L 30/70	9.625	9.625	0	0	9.625	0	0	9.625	0	0
W 70/30	9.523	9.523	0	0	9.523	0	0	9.523	0	0
W 60/40	9.657	9.657	0	0	9.657	0	0	9.627	0	0
W 50/50	9.699	9.699	0	0	9.699	0	0	9.699	0	0
W 40/60	9.628	9.628	0	0	9.628	0	0	9.628	0	0
W 30/70	9.544	9.544	0	0	9.544	0	0	9.544	0	0

Appendix 12: SEM Chemical Analysis

Table 4.7a.1 Chemical Analysis of Drinking Glass Compact fused at 750°C of area marked X

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6089	71.66	72.43	156.65
Na	KA1	1.041	0.0950	14.33	17.68	25.11
Ca	KA1	3.691	0.1145	13.83	9.80	2.74
Fe	KA1	6.403	0.0016	0.19	0.09	1.05
Total				**100.00**	**100.00**	**207.73**

Table 4.7d.1 Chemical Analysis of Drinking Glass Compact fused at 700^{o}C of area marked X_1

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.4920	67.55	67.54	76.95
Na	KA1	1.041	0.0507	7.40	9.03	76.95
Ca	KA1	3.691	0.0142	1.74	1.22	1.13
Fe	KA1	6.403	0.0364	4.30	2.16	1.06
Mg	KA1	1.254	0.0281	3.75	4.33	76.95
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
As	KA1	10.542	0.0020	0.26	0.10	1.46
Al	KA1	1.487	0.1183	15.01	15.62	76.95
Total				**100.00**	**100.00**	**135.54**

Table 4.7d.2 Chemical Analysis of Drinking Glass Compact fused at 700^{o}C of area marked X_2

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6045	71.37	71.94	163.98
Na	KA1	1.041	0.0997	14.93	18.38	34.34
Ca	KA1	3.691	0.1133	13.69	9.67	4.86
Fe	KA1	6.403	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**198.51**

Table 4.7f.1 Chemical Analysis of Fluorescent tube compact fused at 750^{o}C of the area marked X_3 on figure 4.7f

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6161	73.63	73.06	51.03
Na	KA1	1.041	0.0937	13.35	16.18	6.12
Ca	KA1	3.691	0.0639	7.84	5.45	1.12
Fe	KA1	6.403	0.0011	0.13	0.07	0.86
Mg	KA1	1.254	0.0245	3.56	4.08	6.12
Cl	KA1	2.622	0.0093	1.49	1.17	1.29
Total				**100.00**	**100.00**	**90.71**

Table 4.7f.2 Chemical Analysis of Fluorescent tube compact fused at 750^{o}C of the area marked X_4 on figure 4.7f

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6370	75.09	75.10	62.06
Na	KA1	1.041	0.0791	11.50	14.05	5.75
Ca	KA1	3.691	0.0836	10.21	7.15	1.58
Fe	KA1	6.403	0.0000	0.00	0.00	0.00
Mg	KA1	1.254	0.0225	3.20	3.70	5.75
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**54.24**

Table 4.7f.3 Chemical Analysis of Fluorescent tube compact at 750^{o}C of the area marked X_5 on figure 4.7f

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6178	74.06	73.42	69.48
Na	KA1	1.041	0.0949	13.57	16.43	10.29
Ca	KA1	3.691	0.0715	8.73	6.07	1.41
Fe	KA1	6.403	0.0010	0.12	0.06	1.09
Mg	KA1	1.254	0.0241	3.52	4.03	10.29
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**76.66**

Table 4.7i.1 Chemical Analysis of Fluorescent tube compact at 700^{o}C of the area marked on X_6 figure 4.7i

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6644	75.33	78.03	94.97
Na	KA1	1.041	0.0354	5.54	7.01	4.16
Ca	KA1	3.691	0.1362	16.50	11.97	2.20
Fe	KA1	6.403	0.0019	0.23	0.12	1.19
Mg	KA1	1.254	0.0178	2.40	2.87	4.16
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**55.35**

Table 4.7j.1 Chemical Analysis of Laboratory glass compact fused at 750^{o}C of the area marked on X_9 figure 4.7j

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6112	71.15	72.81	167.23
Na	KA1	1.041	0.0789	12.20	15.25	22.21
Ca	KA1	3.691	0.1383	16.65	11.94	6.17
Fe	KA1	6.403	0.0000	0.00	0.00	0.86
Total				**100.00**	**100.00**	**175.99**

Table 4.7m.1 Chemical Analysis of Laboratory glass compact fused at 700^{o}C of the matrix area marked on X_{10} figure 4.7m

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6173	71.31	73.58	131.99
Na	KA1	1.041	0.0665	10.46	13.18	14.97
Ca	KA1	3.691	0.1486	17.87	12.92	4.57
Fe	KA1	6.403	0.0013	0.15	0.08	1.19
Mg	KA1	1.254	0.0014	0.21	0.25	14.97
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**139.10**

Table 4.7m.2 Chemical Analysis of Laboratory glass compact fused at 700^{o}C of the area marked on X_{11} figure 4.7m (pore particle)

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6484	73.50	76.31	190.07
Na	KA1	1.041	0.0502	7.94	10.07	17.74
Ca	KA1	3.691	0.1507	18.16	13.22	4.95
Fe	KA1	6.403	0.0009	0.10	0.05	1.15
Mg	KA1	1.254	0.0021	0.30	0.36	17.74
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**145.07**

Table 4.7o.1 Chemical Analysis of Window glass compact fused at 750^{o}C of the particle area marked on X_{12} figure 4.7o

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.5975	71.16	72.11	145.18
Na	KA1	1.041	0.0751	11.37	14.07	145.18
Ca	KA1	3.691	0.1163	14.07	9.99	3.32
Fe	KA1	6.403	0.0017	0.20	0.10	0.94
Mg	KA1	1.254	0.0218	3.19	3.73	145.18
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
As	KA1	10.542	0.0001	0.02	0.01	1.07
Total				**100.00**	**100.00**	**245.91**

Table 4.7o.2 Chemical Analysis of Window glass compact fused at 750^{o}C of the matrix area marked on X_{13} figure 4.7o

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.6056	71.47	72.86	45.39
Na	KA1	1.041	0.0698	10.72	13.34	45.39
Ca	KA1	3.691	0.1232	14.88	10.63	1.57
Fe	KA1	6.403	0.0035	0.42	0.22	0.85
Mg	KA1	1.254	0.0172	2.51	2.95	45.39
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
As	KA1	10.542	0.0000	0.00	0.00	0.00
Total				**100.00**	**100.00**	**54.00**

Table 4.7p.1 Chemical Analysis of Window glass compact fused at 750^{o}C of the matrix area marked on X_{13} figure 4.7p

Element	Line	keV	KRatio	Wt%	At%	ChiSquare
Si	KA1	1.740	0.8161	89.71	88.70	164.10
Na	KA1	1.041	0.0555	7.55	9.12	164.10
Ca	KA1	3.691	0.0000	0.00	0.00	0.00
Fe	KA1	6.403	0.0096	1.14	0.57	0.96
Mg	KA1	1.254	0.0105	1.33	1.51	164.10
Cl	KA1	2.622	0.0000	0.00	0.00	0.00
As	KA1	10.542	0.0020	0.27	0.10	0.82
Total				**100.00**	**100.00**	**324.31**

Appendix 13; **Compression test results for d1**

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: d1
Interface Type: 4200/4300/4400

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 12.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Humidity (%): 50
Temperature: 23 C

Sample comments: d1 @ 12mm/min speed

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	40.070	0.685	81.630	2.739	-	-	-	-	-
Mean	40.070	0.685	81.630	2.739					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 14; Compression test results for d2

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: d2
Interface Type: 4200/4300/4400

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 12.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Humidity (%): 50
Temperature: 23 C

Sample comments: d2 @ 12mm/min speed

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	22.890	0.484	46.631	0.968	-	-	-	-	-
Mean	22.890	0.484	46.631	0.968					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 15; Compression test results for f1

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: f1
Interface Type: 4200/4300/4400

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 25.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Humidity (%): 50
Temperature: 23 C

Sample comments: 1st sample f1, was 25 mm/min

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at % Strain (kN)
1	37.090	0.737	75.559	2.947	35.959	0.712	73.256	2.847	-
Mean	37.090	0.737	75.559	2.947	35.959	0.712	73.256	2.847	
S.D.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 16; Compression test results for f2

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: f2
Interface Type: 4200/4300/4400

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 25.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Humidity (%): 50
Temperature: 23 C

Sample comments: f2 speed @ 25mm/min

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	40.320	0.814	82.139	1.627	-	-	-	-	-
Mean	40.320	0.814	82.139	1.627					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 17; Compression test results for l1

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: l1
Interface Type: 4200/4300/4400

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 12.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Humidity (%): 50
Temperature: 23 C

Sample comments: l1@ 12mm/min speed

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	40.010	0.650	81.508	2.600	-	-	-	-	-
Mean	40.010	0.650	81.508	2.600					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 18; Compression test results for l2

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: I2
Interface Type: 4200/4300/440u

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 12.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Humidity (%): 50
Temperature: 23 C

Sample comments; I2 @ 12mm/min crosshead speed

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	40.250	0.688	81.997	1.375	-	-	-	-	-
Mean	40.250	0.688	81.997	1.375					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 19; Compression test results for w1

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: w1
Interface Type: 4200/4300/4400

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 12.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Humidity (%): 50
Temperature: 23 C

Sample comments: w1 @ 12mm/min speed

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	40.400	0.664	82.302	2.656	-	-	-	-	-
Mean	40.400	0.664	82.302	2.656					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				

Appendix 20; Compression test results for w2

General Compression Test - S.I. Units

Test type: Compression
Operator name: Pat
Sample Identification: w2
Interface Type: 4200/4300/4400

Sample Rate (pts/secs): 10.0000
Crosshead Speed: 12.0000 mm/min
Second Speed: 0.0000 mm/min
Third Speed: 0.0000 mm/min

Full Scale Load Range: 50.0000 kN

Instron Corporation
Series IX Automated Materials Testing System 8.31.00
Test Date: Monday, May 15, 2006

Humidity (%): 50
Temperature: 23 C

Sample comments: w2 @ 12mm/min speed

	Load at Maximum (kN)	Displcment at Maximum (mm)	Stress at Maximum (MPa)	% Strain at Maximum (%)	Load at Yield (kN)	Displcment at Yield (mm)	Stress at Yield (MPa)	% Strain at Yield (%)	Load at 50% Strain (kN)
1	40.160	0.723	81.813	1.446	-	-	-	-	-
Mean	40.160	0.723	81.813	1.446					
S.D.	0.000	0.000	0.000	0.000					

	Displcment at 50% Strain (mm)	Stress at 50% Strain (MPa)	% Strain at 50% Strain (%)	Energy at 50% Strain (J)
1	-	-	-	-
Mean				
S.D.				