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Optimal Mixture of Materials and Condition in Producing Flat Glasses for Automobile Windscreens in Nigeria

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ABSTRACT: The selection of materials is an essential element for engineering designers. This study investigated the optimal mixture of materials and condition in producing flat glasses for automobile windscreens in Nigeria. To achieve this, 10 pairs of compositions of material mixtures and cullet (broken glasses) were used. The standard material mixture (80/20 wt. % of material mix/cullet) from the local industry was modified to have batches of up to 60/40 wt. % material mix/cullet. These material mixtures were used to produce flat glasses by adopting procedures of industrial float glass process of Pilkington Brothers in variable conditions of annealing temperature and time. The average density of each pair of flat glass was measured using water displacement method, and each pair was later laminated to produce a total of 10 automobile windscreens. The windscreens were subjected to 2.25kg drop ball impact test from a height of 4m at 90^0. The study revealed that the density of the flat glass produced was significantly ($p< 0.01$) related to squared composition (wt. %) of cullet (R^2=97.65%). The highest and lowest densities of 2.23g/cm^3 and 1.95g/cm^3 were obtained at cullet inclusions of 40 wt. % and 20 wt. % respectively at constant annealing temperature (550^0C) and time (60 min). The optimal batch obtained composed of 40 wt. % cullet inclusion, annealed at 500^0C for 50 minutes. Increased cullet composition was found to reduce the melting temperature of the batch mixture and fractured characteristics of the windscreens produced. Employing this design in the windscreens manufacturing industry saves production cost, facilitates a competitive market, enhance the quality of windscreens, reduce emissions and curb environmental degradation.

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Material selection is an essential decision making process for engineering design. This is based on the premise that appropriate material selection is a prospect for durable use of the material and is aligned to unnecessary loss of revenue and lives (Carbone, 2012; Davies, 2012). Consequently, a standard material selection process should capture desired properties and limiting factors for a particular design exercise. With these, systematic and optimisation approaches are employed to facilitate listing of limiting factors associated with design such as strength, hardness, environmental friendliness, cost and availability (Frassine*et al.*,2016; Revitasar and Susanto, 2018). These components that define the selection of materials are then weighed to prioritise more important materials (ranked in order of composite index), and the material with the highest composite index is considered as the best for the application. In the automobile industry, the selection of materials for windscreen production is one of such need for engineering designers. This part of the automobile provides protection to the driver and other occupants, while ensuring clear visibility. To achieve these purposes efficiently, it must possess enough visibility as well as strength to withstand the force of moving air, and other objects. For many industrial

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automobile windscreens, the major components and their proportions are SiO_2 (74-86.8%), Na_2O (4-11.8%) and CaO (6-8.5%) (Civici and Vataj, 2013). These are generally referred to as silica-soda-lime glasses. The variation of the major materials across windscreens has been associated with variation in technologies and the starting materials used for their production. Other materials used and their proportions are Al_2O_3 (0.00-2.77%), K_2O (0.00-0.80%), MgO (0.00-4.71%), MnO (0.001-0.022%), Fe_2O_3 (0.064-0.890%), TiO_2 (0.011-0.115%). The elemental composition (weight %) of these components of windscreen consist of about 50 wt. % Oxygen, 25 wt. % Silicon and 25 wt. % of Na, K, C, Ca, Mg, Al and minor elements. While there are variations in the density of different glasses (2.2 to 3.7g/cm^3), silica-soda-lime glass, the type used for automobile windscreen has density of about 2.49g/cm^3 (Alambra, 2022).Following the purpose for which the material is designed, industrial windscreen manufacturing engineers employ design thinking through rigorous material selection process, applying the economic dynamic of cost benefit analysis (CBA) (Angjusheva *et al.*, 2016; Razzouk and Shute, 2012). To do this, parameters such as environmental friendliness, raw material availability, cost of material, manufacturing process, time savings among others with a view of achieving high quality windscreen and reduce cost are pursued. However, the cost related to replacement of high quality windscreen produced by original equipment manufacturer (OEM) when it becomes faulty is quite huge and challenging to afford, especially for users in poor developing countries such as Nigeria. Faced with this challenge, these users usually make use of windscreens not manufactured by OEM- tend to use locally produced windscreens in semi-automated industry. These industries are making use of some local materials and cullet (broken glasses) obtained from waste collection, hence assisting to achieving financial sustainability in glass recycling (Newlov, 2017). However, such windscreens are usually inferior and vulnerable to cracks and breakage, and their concomitant implication on vehicle users and society. These challenges are some of the problems that impede the progress of the automobile industry in Nigeria (National Automobile Industry, 2015). In this regard, identifying the standard material mix of the local windscreen manufacturing industry and optimise these materials and conditions for windscreen production can enhance windscreen quality, sustain the industry, strengthen local economy and promote environmental health. However, the independent variables that could assist in defining sustainable production with the use of available local materials in this industry in Nigeria remains at infancy. This study, therefore, investigated the optimal mixture of materials and conditions for flat glass production for automobile windscreens in Nigeria.

MATERIALS AND METHODS

Materials and Equipment: A semi-automated glass manufacturing plant at Ogun, State, Nigeria was the site for glass and automobile windscreen manufacturing. The equipment used for production of glass and doubled-layered polyvinyl butyral (PVB) laminated windscreen were: mould, water, cullet (broken glass), float chamber, lehr (special furnace), diamond scribe, bending mould, autoclave, plastic moulding, window fittings, steel ball of various masses, Vernier caliper. The following safety wears were used: safety overall, goggle, booths and hand gloves. The raw materials used for glass manufacturing were: Silica (SiO_2) obtained from sand, sodium oxide (Na_2O) from soda ash, calcium oxide (CaO) from limestone, potassium oxide (K_2O) from potash, Magnesium oxide (MgO), and Aluminium Oxide (Al_2O_3) from feldspar. Most of the equipment was provided by the windscreen manufacturing plant.

Manufacturing of Flat Glass: The standard material composition, measured in weight percent (wt. %), being used by glass manufacturing industries in Nigeria such as the semi-automated glass manufacturing plant at Ogun State was provided by the manufacturing plant (Table 1). This material composition was found to consist of 80 wt. % of material mix and 20 wt. % of cullet.

Table 1. Raw Material Composition of Glass Industry in Nigeria

Raw Materials	Composition (wt. %)
Sand (SiO_2)	46.38
Sodium Carbonate (Na_2CO_3)	15.64
Dolomite ($CaMg(CO_3)_2$)	13.04
Feldspar ($KNaAlSi_3O_8$)	4.30
Cullet	20.09
Alumina	0.5
Total	100

Source: Semi-automated Windscreen Manufacturing Plant, Ogun State, Nigeria.

Table 2. Proportion of Material Mix and Cullet

Batch Number	Material Mix (wt. %)	Cullet (wt. %)
1	80	20
2	75	25
3	70	30
4	65	35
5	60	40
6	75	25
7	70	30
8	65	35
9	60	40
10	75	25

The representative (benchmark) flat glass batch consisting of 80 wt. % material mix and 20 wt. %

cullet (batch 1) were modified with changing material mix and cullet composition (Table 2).

The procedure for flat glass manufacturing was adopted from the industrial float process for the manufacture of glass as designed by Pilkington Brothers (Haldimann *et al*., 2016). The cullet was washed and treated. The treated cullet was washed to finer grain particle size so as to enable proper mixing with sand-silicate-lime mixture. The mixture was dried at 110^0C for a minimum of 24 hours. Each mixture was heated in an electric furnace at a rate of 4^0C/min and the melting temperature for each batch was recorded. Air and other impurities in the mixtures were removed in another chamber in the furnace (conditioning chamber) by a process termed fining of the molten mixture. The molten glass was allowed to pass through a bridge wall into the conditioning chamber where temperature was held at 1500^0C for about 4 hours. It then flowed into the forming chamber narrow channels, a stainless steel or tin mould and allowed to cool until sufficiently rigid to remove the mould. The glass was then annealed at various temperatures and their associated time, and then cooled slowly to room temperature. The process was repeated twice for each batch at various melting temperature, annealing temperature and time. This yielded 20 flat glasses.

The density for each glass was determined by water displacement method and the average for each repeated batch was computed and summarized in g/cm^3. The manufactured flat glasses were paired and laminated to produce a total of 10 laminated automobile windscreens. A drop ball impact test was conducted to determine fractured characteristics along the x and y-axis on all manufactured windscreens and the fractured area (mm^2) was computed. The drop ball impact test adopted the procedure used by Australian/New Zealand Standard Safety Glass for land vehicles –AS/NZS 2080: 1995 (AS/NZS, 1995). The drop ball of 2.25kg was dropped from a height of 4m on each of the manufactured automobile windscreen under the influence of gravity (9.82m/s) at an angle of 90^0.

Data Analysis: Data was analysed using multiple linear regression analysis of Minitab statistical software (version 19.0). It examined how the influence of weight percent of cullet (wt. %), annealing temperature (^{0}C), annealing time (minutes), their significant interactions (independent variables) were related to the dependent variable, density (g/cm^3) of the flat glass produced. The statistical tool is helpful for fitting models and analysing problems in which independent parameters control the dependent parameter(s). Thus, the multiple linear regression statistical tool of Minitab has the elements of response surface model (RSM) following its role in optimization process.

RESULTS AND DISCUSSIONS

Modeling the Design of Flat Glass Production: Table 3 shows the material mix, annealing temperature, annealing time and its associated average density of the pair of flat glass for each batch (process).The statistical analysis of the findings revealed that the density of the glass produced was significantly ($p<0.01$) related to squared percentage cullet in the mixture (Table 4).This interactive effect of cullet (squared percentage composition of cullet) on density means that cullet significantly increased the density of flat glass produced for every unit increase in cullet composition. The model also shows that a unit increase in the percentage composition of cullet tended to decrease the density of the flat glass by 0.0522 g/cm^3, and a unit increase in annealing temperature tended to decrease the density of the flat glass by 0.00081 g/cm^3. However, these were not statistically significant ($p>0.05$).

Table 3. Relationship between Density and Material Mix, Cullet, Annealing Temperature and Time.

Batch	Material Mix (wt.%)	Cullet (wt.%)	Annealing Temp ^{0}C	Time (m)	Average density (g/cm^3)
1	80	20	550	60	1.95
2	75	25	550	60	1.98
3	70	30	550	60	1.99
4	65	35	550	60	2.11
5	60	40	550	60	2.23
6	75	25	500	50	1.96
7	70	30	500	50	1.99
8	65	35	500	50	2.09
9	60	40	500	50	2.2
10	75	25	500	40	1.95

Similarly, a unit increase in annealing time and the interaction effect of cullet and annealing temperature did not significantly ($p>0.05$) increase the density of the flat glass produced. The model shows that the optimal batch obtained (density=2.2 g/cm^3) composed of 40 wt. % cullet inclusion, annealed at 500^{0}C for 50 minutes (Table 3). This means that increasing the annealing temperature and time did not significantly add to the density (Table 4). Consequently, at this point, it is essential to safe resources (time and energy) so as to facilitate and sustain a competitive market in the automobile industry.

Table 4. Regression Analysis of Density of Flat Glass Produced and its Independent Variables.

Term	Coef	SE Coef	T-Value	P-Value
Constant	2.736	0.802	3.41	0.027
Cullet (wt.%)	-0.0522	0.0258	-2.02	0.113
Annealing Temp 0C	-0.00081	0.00152	-0.53	0.623
Time (m)	0.00076	0.00214	0.35	0.742
Cullet (wt. %)*Cullet (wt. %)	0.000822	0.000152	5.40	0.006
Cullet (wt. %)*Annealing Temp 0C	0.000030	0.000039	0.78	0.477

The finding of the study is summarised in a multiple linear regression equation (Equation 1).The variance of the dependent variable explained by the significant independent variables of the model is 97.65% (Table 5). While the R-square (98.96%) shows the contributions of all the independent variables indicated in the model, R-square adjusted (97.65%) explains the contributions made by those independent variables that significantly contribute (squared percentage of cullet) in defining the density of the flat glass produced and optimizing the process.

$$Density\ (g/cm^3) = 2.736 - 0.0522\mathrm{Cullet(wt.\%)} - 0.00081\mathrm{AnnealingTemp0C} + 0.00076\mathrm{Time(m)} + 0.000822\mathrm{Cullet(wt.\%)} * \mathrm{Cullet(wt.\%)} + 0.000030\mathrm{Cullet(wt.\%)} * \mathrm{AnnealingTemp0C}$$
(1)

Table 5. Summary of the Multiple Linear Regression Model

S	R-square	R-square(adjusted)
0.0161589	98.96%	97.65%

Thus, the independent variables, and necessary interaction effects indicated in the model need keen consideration in the design of quality and cost-effective automobile windscreen. This was indicated in the model formulation as addition of independent variables such as percentage material mix and interactive terms such as percentage composition of cullet and time did not substantially improve on the overall fit of the model. Hence, they were discarded in the optimisation and model formulation process for the flat glass density. The increased density of the flat glass produced associated with squared percentage of cullet composition could be attributed to the importance of its content to achieving acceptable quality of automobile windscreen. Cullet (broken glass) is principally made up of silicon, a principal component of glass. However, the proportion of SiO_2 in the local automobile windscreen industries in Nigeria when compared with its proportion in the OEM is quite low (Civici and Vataj, 2013). The low proportion of this content in the local industries challenges the prospect for durability of the product, the economy of the users and the wellbeing of vehicle occupants. Consequently, a keen consideration of increasing the concentration of cullet or related silicon materials will enhance the density and quality of windscreen products in the local industries. This approach is aligned to one of Nigeria's National Automobile Council (2015) key areas of cooperation, upgrading the quality of local products in the automobile industry in order to strengthen efficiency of local production and make them competitive. Thus, squared increase in cullet composition that enhanced the density of the produced glass can assist to achieve this goal in the industry.

Melting Temperature and Drop Ball Impact Test: The melting temperature for each batch of the produced flat glass is summarised (Figure 1).

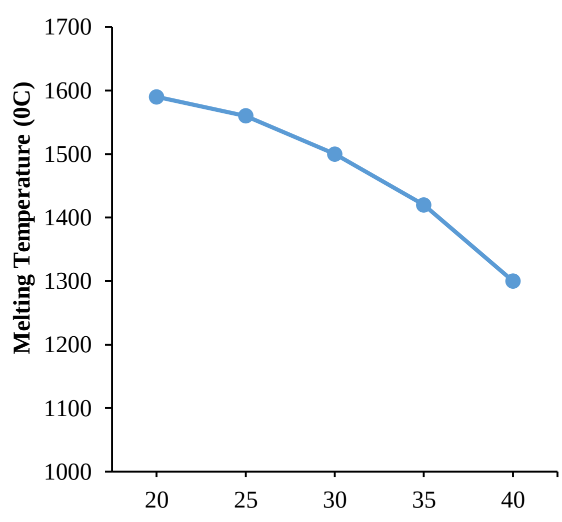

Fig 1. Melting Temperature in Relation to Cullet Percentage Composition in Batch Mixture (wt. %)

It was found that as the weight percentage of cullet increased, the overall batch composition decreased in melting temperature. This is quite impressive in energy savings, reducing emissions associated with burning fossil fuels, transforming waste to wealth and sustaining environmental health. Energy savings is also important in the cost of production, the sustainability of the industry and creation of a competitive market in Nigeria automobile industry (National Automobile Idustry, 2015). This energy saving pathway is in conformity with the global concern for sustainable energy development and achieving environmental health (United Nations, 2020).Therefore, controlled increase in the percentage composition of cullet in local automobile manufacturing industries is beneficial and contributing in achieving sustainable energy development, hence need keen consideration. For the drop ball impact test, it was found that the area of fractured characteristics increased with decreasing density (Table 6). However, all the windscreens produced passed the test as ball did not penetrate the windscreens.

Table 6. Drop Ball Impact Test Showing Area of Fracture Characteristics in Relation to Density.

S/N	Density (g/cm^3)	Fracture characteristics			Test remarks
		Along X-axis (mm)	Along Y-Axis (mm)	Area (mm^2)	
1	1.95	208	209	43472	Passed: ball did no penetrate the windscreen but windscreen damaged
2	1.98	195	200	39000	Passed: ball did no penetrate the windscreen but windscreen damaged
3	1.99	195	205	39975	Passed: ball did no penetrate the windscreen but windscreen damaged
4	2.11	201	184	36984	Passed: ball did no penetrate the windscreen but windscreen damaged
5	2.23	156	169	26364	Passed: ball did no penetrate the windscreen but windscreen damaged
6	1.96	180	189	34020	Passed: ball did no penetrate the windscreen but windscreen damaged
7	1.99	200	200	40000	Passed: ball did no penetrate the windscreen but windscreen damaged
8	2.09	190	199	37810	Passed: ball did no penetrate the windscreen but windscreen damaged
9	2.2	195	191	37245	Passed: ball did no penetrate the windscreen but windscreen damaged
10	1.95	210	205	43050	Passed: ball did no penetrate the windscreen but windscreen damaged

The smallest area of fractured characteristics was 26,346mm^2 for the density of 2.23g/cm^3. This smallest area of fractured characteristics was aligned to 60 wt. % of material mix and 40 wt. % of cullet composition. On the contrary, the largest area of fractured characteristics was 43,472mm^2 and was associated with density of 1.95g/cm^3, aligned to 80 wt. % material mix composition and 20 wt. % of cullet. This means that the density of the flat glass is a direct function of cullet wt. %. According to Alambra (2022), silica-soda-lime glass, the typical type of glass for automobile windscreen should have density of 2.49g/cm^3. This means the density of the flat glass produced at maximum cullet inclusion were very close to the standard. Consequently, the percentage area of fracture of the produced glass is an inverse function of density, which is also dependent on the cullet wt. % mix.

*Conclusion***:** Increasing the weight percentage composition of cullet (broken glasses) in batch mixture for automobile windscreen manufacturing was found to optimise the production process. In the controlled production (annealing temperature and time) of the flat glass, the melting temperature and energy consumption of the batch mixture were reduced. The optimisation pathway achieved has identified specific needs in the Nigeria automobile industry that can contribute in its prospect for quality and competitive market, while ensuring resource savings and environmental health.

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