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Editorial

In this Volume 45 Number 2, the Journal includes nine (9) research and technical articles. The relevance and usefulness of respective articles are summarised below.

L.A. Ellis *et al*., "Investigating the use of Recycled Concrete Aggregates in the Construction of Structural Beams", investigated the use of recycled concrete aggregates (RCA) produced from high strength concrete and its effects on the mechanical properties of concrete and structural members. The results showed that the compressive strength of RCA concrete was 5% greater than natural aggregates (NA) concrete. The influence of the properties of durability and crushing resistance of the RCA, which exceeded that of NA, contributed to the higher concrete strengths when compared to NA concrete. In addition, concrete with RCA and steel fibers had an increase of compressive strength by 16% to concrete without steel fibers. However, no significant increase in the deflection and strain of the beams under third point loading suggest that given the right conditions RCA can be used in place of NA.

In their article, "Port of Spain Commuter Patterns and Satisfaction Levels", **M. Boneo** and **T. Townsend,** reported the first part of a two-stage process of developing a quantitative measure of the performance of the Port of Spain public transportation network. The key stakeholders in the transportation network were identified and classified in a stakeholder matrix on the basis of their interest and influence. A survey was undertaken to understand the public's perception of the transport network and the travel patterns and characteristics. Survey participants were broadly dissatisfied with the transport system, indicating strong dissatisfaction with congestion, lack of accessibility and lack of information experienced in the capital city. The findings also highlighted how disadvantaged users of public transportation are with respect to ease of travel to and within the city.

K. Jackson *et al.*, "Production and Characterisation of a Novel Dasheen (*Colocasia esculenta*) Alcoholic Fermented Beverage", investigated the quality characteristics of two types (i.e., A and B) of dasheen musts, each at three total soluble solids (TSS) levels (18, 22 and 25 ˚Brix). Results showed that fermentation caused pH, SG and TSS to decrease while simultaneously increased TA. Coliforms were not detected in any of the must and fermented beverage samples. The beverage made from batch A, 25 ˚Brix was consumer acceptable based on sensory and physicochemical analyses with a pH of 3.12, SG of 1.0053, TSS of 10.13 ˚Brix, TA (% citric acid) of 0.75% and an alcohol content of 14.00 and 12.52% using the hydrometer and gas chromatography methods respectively. The overall results indicate that this product can be beneficial to the Caribbean food and beverage industries.

Critical Infrastructures (CIs) are essential assets to maintain vital societal functions. The occurrence of faults or attacks in either Cyber domain or Physical domain of CIs could result in the disruption of services, causing negative impacts beyond the system itself. **A. Mohammed** *et al.*, "The Exigency for Resilient and Cyber-Secure Critical Infrastructure in the Caribbean", reviewed past incidents from 2012-2022 taken place both regionally and internationally, with major emphasis on those occurring in the Caribbean region. The article discussed the importance of maintaining resilient and cyber secure CIs for the purpose of critical infrastructure protection (CIP) given the current situation. In responding to frequently occurring scenarios, recommendations on the way forward have been proposed.

In the fifth article, "Fluid Flow and Heat Transfer Characteristics of Clerestory-Shaped Attics Heated from Below", **O. Kamiyo** and **A. Waheed** reported a finite volume analysis of the aerodynamics and heat transfer in attics of a clerestory roof design. It was found that the shape of the enclosure has strong influence on the structure of the flow and temperature fields. The reduction of the number and size of the counter-rotating cells and their formation within the enclosures provide an analogous reduction of the total heat transfer rate as the roof pitch angle increases. The velocity and temperature profiles across midheight and midlength of the enclosures enable the prediction of appropriate position in the attic. On the heat transfer, the relationship between the mean Nusselt number and the Rayleigh number is presented in form of a correlation. The results are of significance to building engineers engaged in the analysis and design of building attics and tropical agriculturalists for the control of produce drying rates.

R.J. Murray, "Energy, Emissions and Exergy Analyses of Ethanol-Biodiesel-Coconut Oil Ternary Fuel Blends and Comparative Assessment of Their Suitability for Compression Ignition Engines", assessed the use of alcohol-biodiesel-vegetable oil blends in compression ignition (CI) engines. Three ethanol-biodiesel-vegetable oil blends were developed using 10%, 20% and 30% alcohol and their performances were compared to diesel and neat coconut oil. These blends were tested in a single cylinder diesel engine and their performances assessed using energy, emissions and exergy analyses. The results indicated that the blends had better brake thermal efficiency (BTE) values than diesel at high to medium loads. The blends were found to be comparable to diesel based on a First Law energy analysis. The Second Law analyses indicated that the blends made better use of their fuel energy potential. The ternary blends would be a viable candidate for future energy conversion via CI engines.

L.P. Leon *et al.*, "Dominating Factors of Road Failures: Perceptions of Key Stakeholders in the Small Island Developing State of Trinidad and Tobago", investigated the reasons for frequent pavement failures and explored their impact on maintenance and economic development in Trinidad and Tobago. A questionnaire was completed by 120 contractors, consultants, and state agency experts specialising in road construction and maintenance. The Relative Importance Index (RII) of the assessment shows that utility cuts by the Water and Sewerage Authority were the most important (0.904), followed by maintenance culture (0.898), quality of work (workmanship) (0.888), poor drainage facilities, and overloaded vehicles (0.854). These would impact on high vehicle running costs, longer travel times, and higher prices for products and services. Recommendations are made to address the critical causes and reduce the adverse consequences of frequent pavement failure.

In the eighth article, "Investigation of Compressive Strength of Slag-based Geopolymer Concrete Incorporated with Palm Oil Fuel Ash", **F.A. Olutoge** and **A.S. Kolade**, investigated the compressive strength of geopolymer concrete incorporated with palm oil fuel ash (POFA). The geopolymer mix entailed fine aggregates, with 100% replacement of portland cement with ground granulated blast furnace slag (GGBS) incorporated with palm oil fuel ash. An alkaline solution was used in place of water containing sodium hydroxide and sodium silicate. Through comparative analysis, it was determined that the most efficient geopolymer mix was mix 2 of GGBS: POFA ratio of 75:25 with 14M alkaline solution. Results showed that geopolymer concrete could achieve greater strength than portland cement concrete.

G. Shrivastava, "A Historical Note of the Department of Civil Engineering, UWI St. Augustine: 1972- 2001", provided a review of the transformations in the Department of Civil Engineering at The University of the West Indies (UWI) at St. Augustine over three subsequent decades. This covered (a) beginning of graduate level research, (b) commencement of an MSc programme in Construction Engineering and Management, (c) change of name from Civil to 'Civil and Environmental', (d) relocation into a purpose built building, (e) construction of environmental engineering, engineering geology, highway engineering, soil mechanics and structural engineering laboratories, (f) expansion and modernization of fluid mechanics laboratory, and (g) introduction of semester system with its credit-based curriculum and assessment.

On behalf of the Editorial Office, we gratefully acknowledge all authors who have made this issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal. Our reviewer panel is composed of academia, and practicing engineers and professionals from industry and other organisations as listed below:

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Investigating the Use of Recycled Concrete as Aggregates in the Construction of Structural Beams

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Abstract: *The World Bank in a decade ago reported a global collective of 1.3 billion tons of solid waste every year with building material accounting for half of this volume annually worldwide. Recycled materials from demolition sites have increased over the years to curtail the demand for natural aggregates (NA). This study investigates the use of recycled concrete aggregates (RCA) produced from high strength concrete and its effects on the mechanical properties of concrete and structural members. Further comparison was made to concrete with steel fibers. The results showed that the compressive strength of RCA concrete was 5% greater than NA concrete. The influence of the properties of durability and crushing resistance of the RCA, which exceeded that of NA, contributed to the higher concrete strengths when compared to NA concrete. Additionally, concrete with RCA and steel fibers had an increase of compressive strength by 16% to concrete without steel fibers. However, no significant increase in the deflection and strain of the beams under third point loading suggest that given the right conditions RCA can be used in place of NA.*

Keywords: *Construction waste; engineering sustainability; recycled concrete aggregate; structural members; steel fiber; waste management*

1. Introduction

Construction and demolition waste (CDW) accounts for the largest contribution to solid waste from a single industry globally (Haung et.al, 2018). The negative environmental and economic impacts of this issue have been a major challenge for the construction industry. Based on the consumption demand for infrastructure and housing, this issue is likely to increase significantly in the future (Limbachiya, 2004). To achieve sustainability, each process within the construction cycle must be evaluated. This has given rise to the Circular Economy (CE), an economic system targeted at eliminating waste and the continual use of resources (Ginga, Ongpeng, and Daly, 2020).

The increase in Construction and Demolition Waste (CDW) is of global concern and one such solution is Waste Management. This process is the collection, transportation, disposal, and recycling of waste. Reusing CDW as aggregates helps to minimise the amount of CDW dumped into the landfills (Ginga, Ongpeng, and Daly, 2020). Dumping of the debris into the landfills in the aftermath of the 12th of January 2010 earthquake in the Republic of Haiti, was not a viable or sustainable option due to the high population density and lack of available land. Thus, the debris was utilised as part of the reconstruction process as a sustainable avenue for Solid Waste Management (DesRoches et al., 2011). In the construction industry, concrete is one of the main composite materials, hence the identification of techniques pointed toward decreasing the environmental impact is critical for achieving the green building goals and sustainable development goals (Merli, 2020), more specifically SDG12 – Sustainable Consumption and Production.

The establishment of international standards such as ISO 13315-1:2012 and ISO 13315-2:2014 (ISO, 2012, 2014) regarding environmental management for concrete and concrete structures demonstrates the global thrust towards managing the negative impacts resulting from concrete production in its various stages. One of the vital components of concrete, cement is a main contributor to greenhouse gases with studies suggesting as high as 8% of the total global Carbon Dioxide (CO_2) emissions (Chandler, 2019). This is contrasted with another major component of concrete, aggregate production, which contributes significantly less than cement production, accounting for 13% to 20% of the total CO_2 emissions of concrete (Braunschweig, Kytzia, and Bischof, 2012). The

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use of natural aggregates is not without faults given the negative effects of riverbed and seaside mining on the ecosystems of local flora and fauna. This gives rise to recycled aggregates (RA) as a suitable replacement. Weil, Jeske, and Schebek (2006)'s research suggests a consumption reduction of about 44%. Marinković et al. (2010)'s study concluded the environmental impact of using recycled concrete aggregates (RCA) in construction will depend on the type of transport used and the distance travelled to obtain NA and RCA.

Another global concern is the reduction of the carbon footprint in construction. The reduction procedure encompasses the substitution of recycled concrete as coarse aggregates in the production of cement concrete, whereby reducing quantities of Natural Aggregate (NA) that are manufactured. The extraction and crushing of NA use more energy and CO_2 than RCA (Behera et al., 2014). Faleschini et al. (2016) examined the environmental impacts of recycled concrete aggregate by conducting a life cycle assessment and analysing the environmental emissions due to the RCA and NA. The results showed that about 50% of carbon can be saved by using RCA instead of NA.

One major argument is that RCA is inferior in strength when compared to concrete produced with natural aggregate (Limbachiya et al., 2000; McNeil et al., 2013; Fiol et al., 2018). However, other studies have found the inverse indicating that the crushing value of RCA was higher than that of virgin aggregates. Parthiban and Mohan (2017) study on RCA with 100% replacement of NA presented very good performance. This was achieved by pre-wetting and saturating the RCA, as well as using superplasticizers to avoid negative effects such as reduced workability and poor mechanical performance. Although RCA has been classified as low quality material research, such as Arulrajah et al. (2012) and Jayakody et al. (2014) have undertaken laboratory bearing capacity testing research, with the results indicating that RCA satisfied the criteria for use in pavement sub-base applications. Typically, the quality of recycled concrete aggregates is usually lower than the quality of virgin aggregate which is a significant consideration for the application of structural concrete (Marinković, 2010).

The old, adhered mortar in RCA reduces its concrete composite strength and during the crushing process micro-cracks are formed (Behera et al., 2014; Kosior-Kazberuk and Grzywa, 2014). The old mortar on the RCA breaks off easily in the weak area in concrete found in the Interfacial Transition Zone (ITZ). NA do not have this coating; thus, they attach to the cement better, creating stronger bonds and increasing the overall strength of concrete (McNeil and Kang, 2013). Monrose et al. (2020) further examined the micro-structure and bonding ITZ of cementitious NA using a scanning electron microscope (SEM). Results indicated that the cementitious paste appeared to be homogenous and dense with solid bonding between the two phases. Though micro-cracking (<2 μm) was observed it was reportedly limited to the bonding zone.

Notwithstanding, RCA has aggregate property deficiencies comparative to NA, it can still meet its proposed purpose as replacement coarse aggregate in the production of cement concrete on the grounds that the quality characteristics are kept within the specified design limits (Lee 2013). Furthermore, research such as Limbachiya et al., 2000; Malešev et al., 2010; Marinković, 2010; McNeil et al., 2013; Fiol et al., 2018, all focused on RCA that were weaker than NA. A few researchers (such as Smith (2018)) have investigated the behaviour of concrete with high-strength RCA. Limbachiya et al. (2000) study indicated that coarse RCA can be used in a range of high-strength concrete mixes with satisfactory engineering properties, namely compressive strength, flexural strength, and modulus of elasticity. However, shrinkage and creep strains were found to increase with RCA content in the concrete. Due to the lack of empirical evidence in this area, this study sought to investigate the behaviour of structural concrete produced with 100% replacement of coarse RCA that are equal or exceeded the mechanical properties (hardness and strength) of NA.

Kosior-Kazberuk and Grzywa (2014) suggested that RCA can be used in making non-structural members such as foundations and sub-base layers in pavements. Malešev et al. (2010) suggested that beams made of RCA performed similarly to NA concrete. A successful example of RCA for structural applications is the construction of the Samwoh Eco-Green Building in Singapore which utilised a 100% recycled concrete aggregate (Ho et al., 2015).

Concrete is known for its low tensile strength and ductility. To resist the stress and strains in structural members, reinforcement is added. Various international institutions, such as American Concrete Institute (ACI) and the American Society of Civil Engineers (ASCE), and numerous scholars have recommended the use of steel fibers as an effective way to increase tensile strength of concrete and the ability of resistance to cracking and crack propagation (Chanh, 2005; Biolzi, and Cattaneo, 2017; Lee et al., 2018; Aslani et al. 2019; Chalioris et al., 2019). Steel fiber RCA concrete was suggested by Gao (2019) to have good durability and can be successfully applied to structural members with proper mixture design. Steel fiber reinforced concrete (SFRC) is a composite material made with cement, aggregate, additive, and incorporating discrete discontinuous steel fibers (Zhang et al., 2017). The results of studies conducted by Zhang et al. (2017) show that steel fibers can improve splitting tensile strength of concrete. Other scholars such as Zheng et.al (2018) also show that in SFRC with more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

With the increase in steel fiber content, all these mechanical properties (such as compression strength, flexural strength, and splitting tensile strength) improve

gradually, especially for flexural strength and splitting tensile strength, the steel fiber reinforcement effect is obvious. At the same fiber content, reinforcement effect of mechanical properties of high-strength concrete is better (Zheng et al., 2018).

FRC offers several advantages over rebar or wire mesh reinforced concrete which include energy absorption, impact resistance and residual strength. Chanh (2005) added fibers to concrete beams, thereby increasing the compressive strength by 25%. Further to that, assuming that the fibers are randomly distributed, steel fibers can increase the tensile strength by 60%. Research by Smith et al. (2014) also highlights that strategically laying out steel fibers in a preferred direction increases the carrying capacity up to 4 times. The use of fibers in concrete also proved to be very effective in reducing the carbon footprint and cost of reinforcement structural concrete, as well as being eco-friendly and economical than conventional concrete for the same load-carrying capacity (Ali et al., 2020).

In Trinidad and Tobago (T&T), there are three major waste disposal sites, collectively receiving approximately 2,000 tons/day of Municipal solid waste, however, none of which operates as a sanitary landfill (Riquelme, Mendez, and Smith, 2016). Therefore, the use of RCA will contribute to recycling of this disposal material in landfills. The use of RCA in T&T is minimal due to the impurities and defects associated with the aggregates (Lalla and Mwasha, 2014), limiting its application to road filling in the country. However, waste from construction sites, such as RCA, can be recycled and reintroduced into the building life cycle. In a controlled study by Lalla and Mwasha (2014), using RCA from a concrete laboratory, the results indicated the compressive strength (CS) of RAC was comparative to that of its source material with a batch of 25% replacement.

While numerous recent studies (Bui et al., 2018; Wijayasundara et al., 2018; Chen, 2019; Rashid et al., 2020; Munir et al., 2020) examined incorporating RCA concrete in construction, there is a scarcity of information on the utilisation of coarse RCA as 100% replacement of NA. Further, the inclusion of steel fibers in concrete has provided promising results in improving its structural capabilities such as ductility, crack resistance, and flexural strength (Johnston 2001; Kosior-Kazberuk and Grzywa, 2014). Therefore, this study aimed to investigate the effects of RCA concrete on the mechanical properties (compressive strength, flexural behaviour, failure modes, strain and deflection) of structural members with and without the addition of steel fibers.

2. Experimental Programme

Various eco-productive NA and RCA concrete mixtures with and without steel wire fibers were manufactured. The properties of the ingredients utilised, mixture proportions, specimen preparation, and mechanical testing procedures are described below.

2.1 Materials

2.1.1 Portland Cement and Water

As was the case in Lalla and Mwasha (2014), a sample of Portland-Pozzolan Cement manufactured at Trinidad Cement Limited (TCL) was used. Table 1 shows the component and physical properties of the TCL Type 1 cement used. This type of cement, contains 15-40% by weight of pozzolan (fly ash). Natural (i.e., ordinary tap water) pipe borne water was used. Local tap borne water in Trinidad is slightly acidic. The content of humic and organic acids was at minimum. Portland cement of Grade 42.5N conforming to BS EN 197-112 (BSI, 1990) was used throughout the study for concrete production.

Table 1. Components and Physical Properties of the TCL Type 1 Cement

Component Name	%	Cas No.
Tri-calcium silicate	15-25	12168-85-3
Di-calcium silicate	75-85	10034-77-2
Tetra-calcium-alumino-sulphate	10-15	12068-35-8
Calcium sulphate	1-4	13397-24-5
Tri-calcium Aluminate	7-10	12042-78-3
Calcium Carbonate	0-5	1317-65-3
Magnesium Oxide	0-3	1309-48-4
Calcium Oxide	0-1	1305-78-8
Chromates	0-0.005	
Physical data *pH (in water) – 12 to 13* *Solubility in water – Slight (0.1 to 1.0 %) Specific gravity - ~3.04* *Appearance and Odour – solid, grey powder; no odour.*		

Source: TCL (2020)

2.1.2 Steel Fibers and Superplasticizer

Hooked end steel fibers, commercially known as Dramix-Type ZC, was used in this study. These fibers were 50 mm long and 0.5 mm diameter (aspect ratio, l/d = 100), as shown in Figure 1. Zhao et al. (2009) observed the tensile strength of the SFRC was enhanced more by steel fibers with a higher aspect ratio, since this improves the fiber-matrix bond. A superplasticizer (Conplast SP423) was added to ensure uniformity and fluidity in the recycled concrete mixtures.

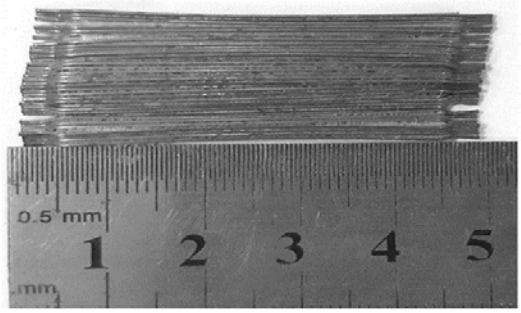

Figure 1. Dramix ZC 50/50 End Hooked Steel Fibers

2.1.3 Natural and Recycled Aggregates

The characteristics of the materials utilised in the investigation are highlighted in Table 2. The virgin aggregates used were 19 mm quartz and natural sand. Given the challenges experienced in procuring concrete demolition, the recycled concrete aggregate used in this research was produced from high strength concrete samples designed at The University of the West Indies having compressive strength greater than 35 MPa (nominal at 28 days) as indicated in Figure 2. The concrete samples were hammered to smaller sizes and then further crushed using a mechanical crusher to produce the required RCA aggregate sizes. The final gradation was selected after a continuous sieving process which was simultaneously done throughout the crushing process. The goal was to achieve a gradation similar to that of the existing available natural aggregate.

Figure 2. Recycled Concrete Cubes and Cylinders Used

Table 2. Fundamental Properties of the Aggregate Materials

Properties	NA	RCA	Test Standard
Water Absorption %	0.9	7.7	ASTM C127*
Particle Density (SSD) (mg/m^3)	2.58	2.33	ASTM C127*
Aggregate Impact Value (AIV) %	40	31	BS 812-112
Aggregate Crushing Value (ACV) %	42	32	BS 812-110
Load required for 10 percent fines (TFV) (kN)	71	77	BS 812-111
Voids Ratio (%)	44.3	46.8	ASTM C29*
Unit Weight of aggregate (kg/m^3)	1420	1173	ASTM C29*
LA Abrasion (%)	35	34	ASTM C131*

* - Sources: ASTM (2015, 2017, 2020)

This research observed RCA with a higher TFV than that of NA. The RCA were able to withstand a greater load to produce 10% of fine values. As indicated in Table 2, RCA is harder than the NA based on these tests and less breaking down of the RCA was observed. Researchers such as Silva et al. (2014) have similarly indicated that low AIV values indicate aggregates that are tougher and able to withstand more impact. Both the coarse NA and RCA aggregate met coarse aggregate particle distribution as highlighted in Figure 3. The gradation of the RCA is similar to that of the natural crushed-rock aggregate; however, it was very porous, angular and coarser than natural aggregate. Moreover, RCA had an average of 9% lower relative density and seven times higher water absorption than NA.

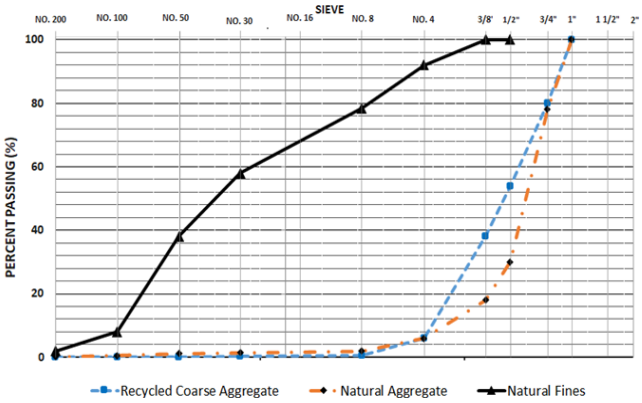

Figure 3. Aggregate Particle Distribution

2.2 Mixtures

As indicated in Table 3, the concrete mixture used in the study was all prepared using the mix ratios of water-to-cement of 0.44, fine-to-coarse of 0.4, total aggregate-to-cement of 3.38 and steel fiber-to-coarse aggregate to 0.016. The coarse aggregates consist of 67% of the total aggregates, thus the RCA replacement was 67% of the total aggregates. This is a 2:1 ratio for coarse-to-fine aggregates. Mix proportions were calculated based on the total mass of the samples. For all mixtures with steel fiber, a 0.4% superplasticizer quantity (by weight of cement) was sufficient to warrant the specified efflux time. The steel fibers were randomly distributed in the mix which aid in reducing the mixing and preparation time for test samples. Table 3 shows the mix types and combinations of materials used in the study.

Table 3. Natural and Recycle Concrete Mixture Proportions

Materials / Mix Type	Concrete with RCA	Concrete with NA	Concrete with RCA + steel fibers	Concrete with NA + steel fibers
water /l	16.6	15.6	15.2	15.9
cement /kg	37.8	36.2	34.7	36.2
fines /kg	51.1	49.0	46.8	49.0
coarse /kg	76.6	73.4	70.2	73.4
superplasticizer/ml	193	-	180	-
Steel Fibers /kg	-	-	2.7	2.7

2.3 Experimental Procedure

A total of sixty 150 mm∅ and twenty 100 mm∅ cylindrical samples were prepared for testing as per the ASTM C192 (ASTM, 2014). As per ASTM C39 (ASTM, 2021), the compressive strength testing was conducted on all cylinders at 7 and 28 days using the Triple Dial Face Hydraulic Compression Testing Machine. At day 7 curing, 2-100 mm∅ and 2-150 mm∅ cylinders were used, and at day 28, 3-100 mm and 3-150 mm cylinders. Cylinders were capped with Sulphur before they were crushed thus providing a smooth, even surface for loading. The compressive strength, density and failure modes were recorded.

The flexural strength of all the concrete mixtures was investigated using the three-point bending test method of ASTM C78 (ASTM, 2022), as highlighted in Figure 4. This test examined in detail the deflection, strain patterns and cracking of beams due to loading. Beams were tested after 28 days and were painted white to allow ease in identifying cracks. On the front face of the beams, demec points were placed to measure the strain in the beam during loading done at 5kN increments. Demec points were placed in a 3x3 grid pattern on the beam as shown in Figure 4, located on the top, middle and bottom of the beam.

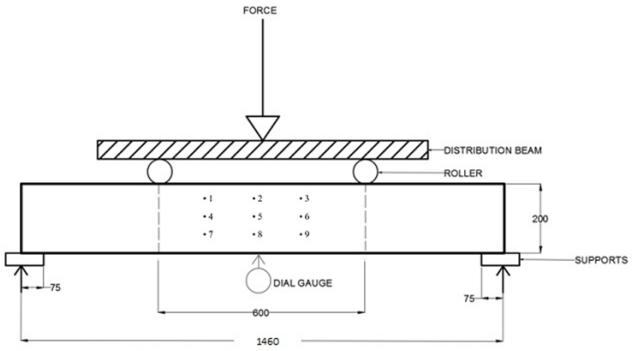

Figure 4. Third-point Loading of Reinforced Beam with 9 Demec Points

The points were spaced 100mm apart along each vertical line on the surface of the beam. The rows were placed 50mm apart, 50mm from the top of the beam. The 2 displacement readings are averaged together to create one displacement reading at the bottom, middle and top of the beam. These values were used to determine the beam compression and tension zones. Assuming the neutral axis is at the center of the beam since the concrete is of a homogenous mixture, a dial gauge was placed at midpoint below the beam to measure the deflection of the beam during loading. The initial deflection of the beam with no loading was set to zero on the dial gauge. Loading was done at a constant rate breaking point, which occurs when the deflection gauge fluctuates.

3. Results and Discussion

3.1 Bulk Properties of Concrete

Figure 5 illustrates the average bulk density of the tested mixtures. Concrete fabricated with RCA has a lower density than NA concrete. The attached mortar on the RCA causes the aggregates to be lighter than NA, which consequently produces densities that are much lower than NA (Behera et al., 2014; Kosior-Kazberuk and Grzywa, 2014). It was also observed that concrete made with NA+sf, and RCA+sf was denser than NA and RCA. This is due to the steel fibers that increase the overall weight of the concrete, thus increasing the density. This general trend was also found by McNeil and Kang (2013) and Ho et al. (2013).

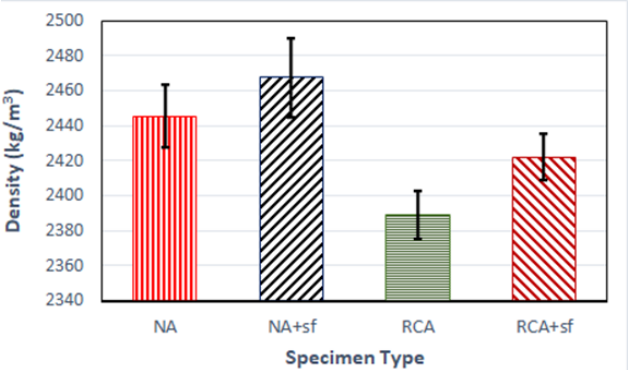

Figure 5. Average Bulk Densities of Mixtures

3.2 Concrete Compressive Strength

Figure 6 illustrates the average 7 and 28 days' compressive strength of both the 100 and 150 mm diameter samples for each of the various mixes. Mindess, Young and Darwin (2003) give a general rule: The ratio of 28-day to seven-day strength lies between 1.3 and 1.7 and generally is less than 1.5, or the seven-day strength is normally between 60% to 75% of the 28-day strength and usually above 65%. In the case of this study, the compressive strength for both NAC and RAC ranged between 1.1 and 13. RCA properties as shown in Figure 6 have a higher compressive strength than NA, which also mirrors the results from the mechanical properties of the aggregates. The range of increase was between 0 – 25%. This finding is not typical as noted by McNeil and Kang (2013); however, this study used a non-traditional source of RCA, that being from a University concrete laboratory as opposed to a demolished structure. The smaller diameter (100 mm) specimens had lower compressive strength than the larger diameter. This can be correlated to the surface area accuracy in determining the compressive strength. A 100 mm diameter cylindrical concrete sample has a lesser surface area thus requiring a lesser amount of load to break the cylinder for the same compressive strength of concrete. However, 150mm concrete cylinders have a greater surface area hence more weight has to be applied to the concrete cylinder to get the required similar compressive strength.

The RCA mixes had a 5% increase in compressive strength compared to NA, while fiber reinforced RCA had a significant increase of 28% to fiber reinforced NA concrete (NA+sf). Fiber reinforced NA concrete (NA+sf) had a 4% increase in compressive strength when compared to NA concrete without steel fibers. Whilst research by Chanh (2005) and Kosior-Kazberuk and Grzywa (2014) found that fibers do not significantly increase compressive strength of concrete, this was not the case in this study. Additionally, as indicated by Smith et al. (2014), further increase in the fiber concrete compressive strength could have been achieved had the steel fibers been strategically laid out by varying the lengths and placing in preferred direction.

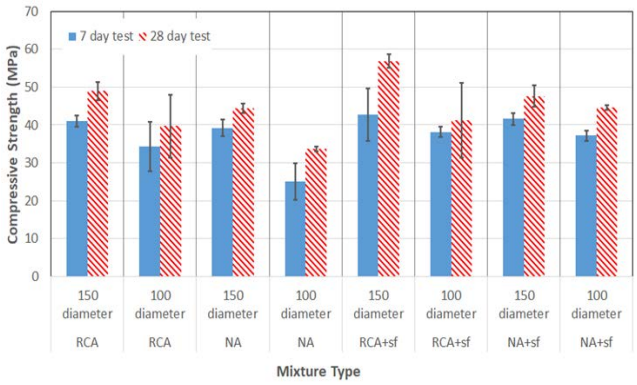

Figure 6: Average Compressive Strength of Mixtures

3.3 Concrete Beams Failure Patterns and Modes

The patterns and mode of specimens' failure were influenced by the steel wire fiber content. Like failure patterns by Kosior-Kazberuk and Grzywa (2014), the shape of the fiber reinforced concrete specimens remained the same under destructive load. Table 4 summarises the failure modes of the samples, as per ASTM C39 (ASTM, 2021).. The NA and RCA concrete made without steel fibers showed similar columnar, shear and splitting failure modes. NA concrete had greater fracture than RCA, which can be the consequence of the mortar coating on the RCA that causes the aggregates to fail at the ITZ (Behera et al., 2014; Kosior-Kazberuk and Grzywa, 2014; McNeil and Kang, 2013).

Table 4. Summary of Failure Types of Concrete Cylinders

Concrete Type	NA	NA+sf	RCA	RCA+sf
100mm	Columnar; Shear;	Column;	Column; Shear;	Column;
150mm	Cone and split; Aggregate failure; Bond failure; Cone and shear; Large cone deformation;	Shear;	Aggregate failure; Shear and cone; Cone and split;	Shear (spiral);

Figure 7 gives a visual depiction of the failure modes and patterns of the 100, 150 mm diameter cylindrical specimens at 28-day strength. RCA had a larger failure region than the NA, although the RCA concrete was more resistant to compression. NA samples mainly experienced bond failure, where the cement paste split from the aggregate. The samples with steel fibers maintained their shape when subjected to axial loading, regardless of the aggregate type. This finding may be attributed to the steel fibers ability to increase splitting tensile strength, especially in SFRC with more than 1% (Zhang et al., 2017; Zheng et al. 2018).

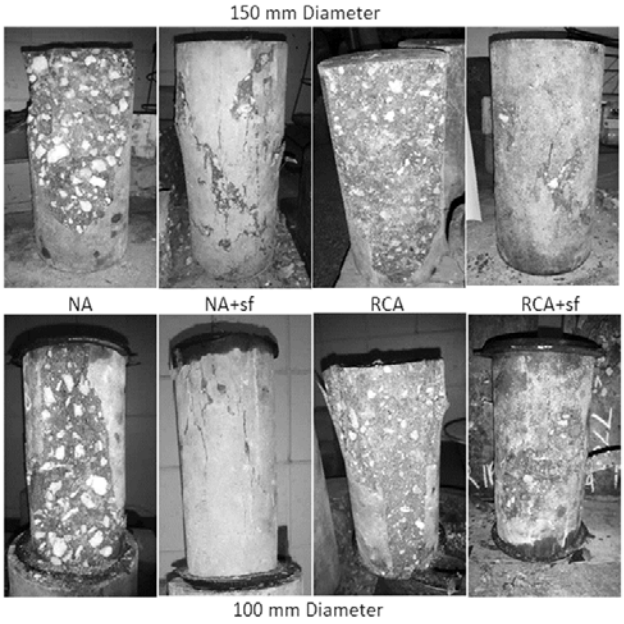

Figure 7. Failure Modes and Patterns of Cylindrical Concrete Specimens

3.4 Flexural Behaviour

To evaluate the tensile behaviour and patterns of the concrete, a total of 12 beams were tested using third-point loading. Evaluation of strain, deflection and cracking pattern were recorded. At the initial cracking at the load of 15kN, similar patterns were observed. This was a subjective analysis, done by observation. The average failure loads of the NA, NA+sf, RCA, and RCA+sf were 55 kN, 67 kN, 60 kN and 67 kN, respectively.

As the loading increased, the width of the cracks also increased. Beams made with NA had less visible cracks when compared to beams with RCA. Therefore, it can be concluded that the steel fibers in RC beams increase the number of cracks and decrease the average crack width due to the higher ductility behaviour of SFARC beams.

As commonly observed in numerous studies (Chanh 2005; Biolzi and Cattaneo, 2017; Zhang et al., 2017; Lee et al., 2018; Aslani et al., 2019; Chalioris et al.,2019), the samples with steel fibers experienced a reduced cracking width regardless of aggregate type as shown in Figure 8.

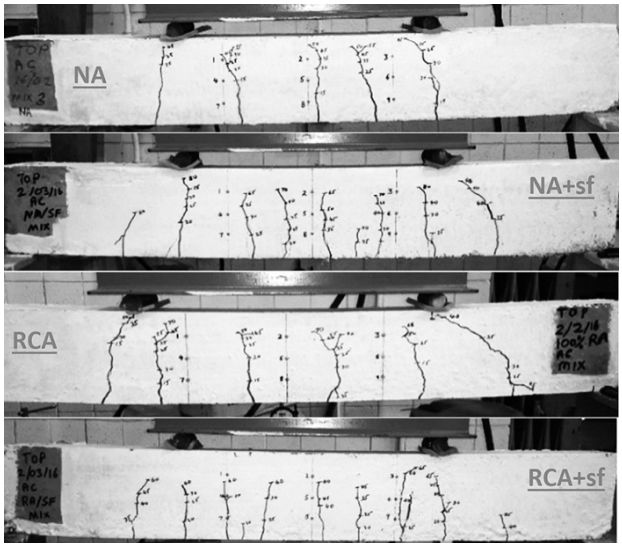

Figure 8. Cracking Patterns for Concrete Beams

3.4.1 Strain

Based on the strain values, all 12 beams experienced compression to the top and tension to the bottom. A reduction in the strain values on the first row of demec points infer compression and an increase in the strain values in the bottom row infer tension. The row in the center (neutral axis) had an increase in strain, hence it experiences tension. It was observed that the concrete beams fabricated with steel fibers measured less strain than beams without steel fibers. Furthermore, tension cracking and strain decreased as the steel absorbed energy and bridged cracks. The strain-load shown in Figure 9, indicates significant changes in strain at the middle and bottom of the beams as load increases.

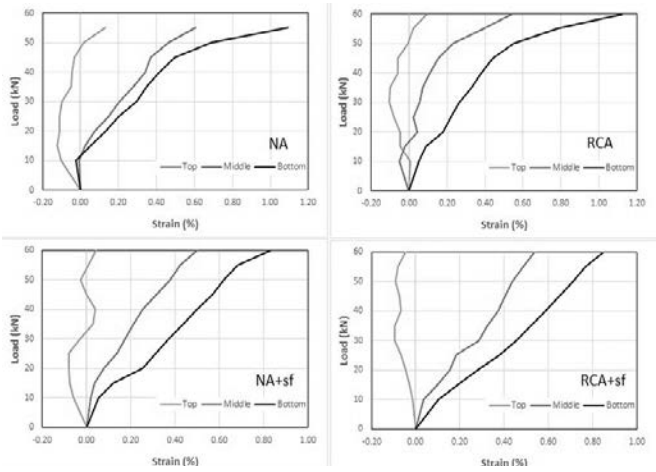

Figure 9. Load vs Strain Curves for Concrete Beams due to Flexural Loading

3.4.2 Deflection

Beam deflection was measured at midpoint and the values for each RCA and NA mix was plotted in Figure 10. The results show the consistently higher resistance to deflection of RAC with steel fibers to loading when compared to RAC without steel fibers. Lok and Pei (1998) and Kosior-Kazberuk and Grzywa (2014) also found that the steel fibers caused the beam to be more ductile given the reduced level of cracking. The beams made with SF had an average failure load of 60kN and above as compared to the beams made without, failing at 55kN. Hence, RCA could be used as a replacement for NCA when SFs were used, with no considerable reduction in the tensile strength.

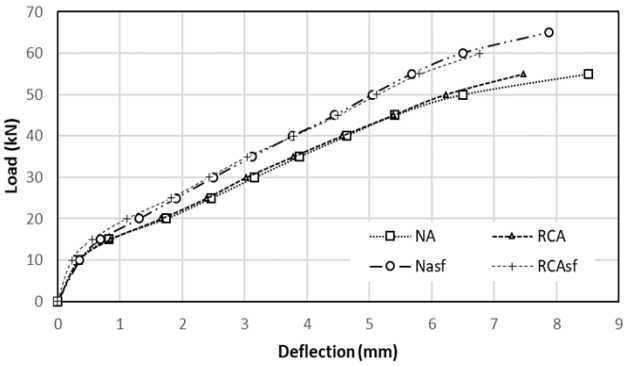

Figure 10. Load vs Average Deflection for Concrete Beams

4. Conclusion

This research was conducted to investigate the effects of RCA use on the mechanical properties of concrete (compressive strength, failure modes, flexural behaviour, strain and deflection) and the impact of RCA on structural members with and without the addition of steel fibers.

Customarily, NA concrete compressive strength exceeds that of RCA concrete, however, this study revealed the inverse. This was true for both RCA concrete with and without SF. This was attributed to the high strength RCA being sourced from a concrete laboratory as opposed to the typical demolished structure. Nonetheless, this finding shows the potential for concrete with 100% RCA and RCA_{sf} to be used in structural members.

Under axial compression, the common failure modes were splitting or columnar failures in 100mm∅ cylinders and shear failure in the 150mm∅ cylinders. However, cylinders with SF revealed less types of failure modes than those without. This was attributed to the SFs capability to increase splitting tensile strength, particularly in SFRC with more than 1%.

The flexural behaviour of twelve reinforced concrete beams being influenced by SF was examined using the third-point loading test method to determine the strain and deflection of the structural members. The average failure loads of NA, $NA_{sf,}$ RCA, and RCA_{sf} were 55kN,

67kN, 60kN, and 67 kN, respectively. Based on the data obtained, structural members fabricated with steel fibers measured a decrease in tension cracking and strain because of the ability of the steel fibers to absorb energy and bridge cracks. The general trends observed indicate that coarse RCA with strengths higher than NA and the combinations of steel fibers can be used to produce high strength concrete mixes. This shows satisfactory improvements in the engineering properties, namely compressive strength, flexural strength, strain and deflections.

The properties of the high-strength coarse RCA, obtained from concrete laboratory waste cylinders and cubes, can be used in high strength concrete and structural members. However, the suitability and effects of varying strengths of RCA should be examined in future studies. Changing the RCA strength from weak to high strength Portland cement concrete can map the effects of RCA strength on mix behaviour. Likewise, it is vital to acknowledge that there should be a move to introduce new standards for recycled aggregates use and illustrate that these materials can be used utilised effectively in practice, under a range of various conditions.

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Port of Spain Commuter Patterns and Satisfaction Levels

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Abstract: *Port of Spain (POS) functions as the administrative, political, and commercial capital of Trinidad and Tobago, attracting many commuters daily. This paper reports the first part of a two-stage process of developing a quantitative measure of the performance of the Port of Spain public transportation network. It provides insight into the key stakeholders and the needs, preferences, and satisfaction of users of the Port of Spain transportation network. The key stakeholders in the transportation network were identified and classified in a stakeholder matrix on the basis of their interest and influence. A survey was undertaken to understand the public's perception of the transport network and the travel patterns and characteristics. The results suggest that while most trips to and within Port of Spain are completed for employment, a significant percentage is for personal business and shopping/leisure. Moreover, while the largest number of trips ended in the central business district (CBD) of Port of Spain's most destinations are outside the CBD. Survey participants were broadly dissatisfied with the transport system, indicating strong dissatisfaction with congestion, lack of accessibility and lack of information experienced in the capital city. Indeed, a minimum of forty-four percent and a maximum of seventy-eight of respondents were either dissatisfied or very dissatisfied with some aspects of the transport system. No more than twenty-five percent, and in the case of congestion only three percent, of respondents were either satisfied or very satisfied. Although transport safety received the least negative response among the transport indicators, approximately forty-six percent of respondents were dissatisfied or very dissatisfied with it. Also, in general, females reported more dissatisfaction with transport safety compared to men. The findings also highlighted how disadvantaged users of public transportation are with respect to ease of travel to and within the city. This paper reports on the mapping of the network and the development of a performance index.*

Keywords: *Commuter surveys, Stakeholder engagement, traveller perceptions, Port of Spain, Trinidad and Tobago*

1. Introduction

The Republic of Trinidad and Tobago is located within the south-east zone of the Caribbean. This twin-island nation has a population of 1.3 million (Central Statistical Office, 2012), a gross domestic product (GDP) per capita of US$15,424 (The World Bank, 2020) and motorisation of 583 vehicles per thousand people (Bollers et al, 2019). Its capital city, Port of Spain (POS) covers an area of 12.3 km^2 and functions as the administrative, political, and commercial capital of the country.

Businesses within this municipality cover a wide range of sectors. The predominant sectors consist of retail and distribution, finance, insurance, real estate and business services (Kairi Consultants Limited, 2016). As a result, the area attracts many commuters daily. Movement of this predominantly transient population is facilitated by private vehicles, public transportation providers and non-motorised methods such as walking. Public transportation is provided by taxis, maxi-taxis, Public Transport Service Corporation (PTSC) buses and Transportation Network Companies (TNCs). Taxis are 4 to 9-seater cars registered to convey multiple passengers between locations of choice. Registered taxis are identified by the first letter "H" on the license plate. Fares are not metered but instead, a fixed fare is assigned to each route. On several routes, private vehicle owners illegally operate as taxis, in competition with the registered taxis. These are called 'PH taxis'.

Maxi-taxis are privately owned 9 to 25-seater minibuses (OBG, 2016). They are painted off-white with horizontal bands at the mid-portion of the vehicle in the colour assigned to its respective route area (MAGLA, 2016). Maxi-taxis operate within fixed geographical areas and have fixed stands but their routes within their assigned areas are not fixed. Maxi-taxis do not operate on a fixed schedule. Fares for any given route are fixed by the associations of operators. Rides are shared with others who are picked up and let off along the route.

The PTSC is a state-owned, bus service company governed by the Public Transport Service Act, Chapter

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48:02 of Trinidad and Tobago. The organisation provides national bus transport, chartered bus service, contracted school transport and specialised transport for persons with disabilities. The buses carry passengers along fixed routes for fixed fares.

'Drop', 'TT RideShare', 'PinkCab', 'RideConnect' and 'Caribbean Taxi' are examples of Transportation Network Companies operating in Trinidad. Transportation Network Companies (TNCs), also known as ride-sharing companies, provide on-demand transport services for passengers. Passengers request a ride and are matched to private drivers under contract with the TNC through a mobile application.

This paper identifies the key stakeholders of the POS transportation network and examines the travel patterns, preferences, and satisfaction levels of the transport users of the identified network. Focus was given to the transport users, since analysis of user experiences and user perceptions is critical in advocating to stakeholders with greater influence.

2. Challenges Associated with the Port of Spain Transportation System

Extant research confirmed that the Latin American and Caribbean urban transport environment is characterised by high private transport usage, high congestion rates, long commute times and a limited distribution of information related to routes and schedules.

Leung (2009) and Bollers et al. (2019, p.24) presented evidence of these challenges in Port of Spain. As of 2001, 221,000 private vehicles entered the capital city of Port of Spain transporting 330,000 individuals daily (Leung, 2009). As shown in Figure 1, these private vehicles represented 85% of the total number of vehicles entering the city. The other 15% consisted of 39,000 public transport vehicles (PTSC buses, taxis and maxi-taxis) which transported approximately 270,000 persons (Leung, 2009).

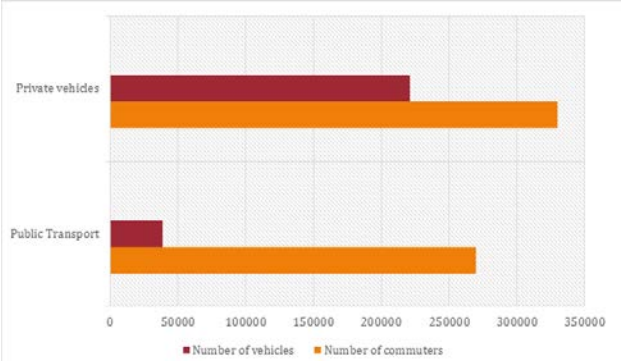


Figure 1. Daily Distribution of Vehicles Entering Port of Spain based on 2001 Study. Source: Adapted from Leung (2009)

More recently, the Inter-American Development Bank (IDB) reported that a total of 260,000 vehicles entered the capital city daily (Bollers et al., 2019, p.24). This suggests a seventeen percent (17%) increase in the number of vehicles entering the city from 2001 to 2019. In addition, the IDB highlighted that Trinidad has a motorisation rate of 583 vehicles per 1000 persons, the highest in the Caribbean (Bollers et.al, 2019).

The occurrence of crime, lack of public information on available public transport routes and the public's poor perception of the public transport services provided, all contribute to this high private vehicle usage in the capital (Leung, 2009). As a result, the city experiences increased congestion, limited parking and a reduction in productivity (Leung, 2009). Accordingly, the IDB highlighted that the inadequacies in the road transport system cost users an estimated US$267-345 million annually in lost time, reliability and fuel (Bollers et. al., 2019).

Measures to mitigate these negative features of the urban transport environment must be developed, deployed and evaluated. However, before solutions can be applied, an understanding of its organisation and performance in addition to the stakeholder experience must be examined.

3. Stakeholder Identification, Classification and Categorisation

Transportation policies are multi-agent and multi-sector in nature (Haial et al., 2017). A wide range of interests and issues must be considered. The major stakeholder groups that can impact or are impacted by transport strategy development fall under the main headings of government or authorities, businesses or operators and users of the transport system. Through the explanation of a three-component stakeholder analysis model, Kivits (2011) demonstrated how to achieve an in-depth understanding of stakeholder groups. The model involved classifying and categorising each stakeholder group based on salience, how the stakeholder viewed the world and the relationships among stakeholder groups.

The fundamentals of stakeholder analysis outlined by Kivits (2011, p.321) were further supported by Bossche et al. (2017). In the context of urban freight logistics policy development and implementation, van den Bossche et al. (2017, p. 16) considered stakeholder classification based on the stakeholder's influence, level of interest, contribution, legitimacy and, the relationship among stakeholders.

Figure 2 demonstrates how van den Bossche et al. (2017, p.16) categorised urban freight stakeholders using influence and interest. This is useful to understand the relationships amongst stakeholders as well as the level of engagement required by each stakeholder group. Accordingly, this research project adapted the Kivits (2011, p.329) model and van den Bossche et al. (2017, p.16) approach by classifying stakeholders according to salience, level of interest and relationships among stakeholders.

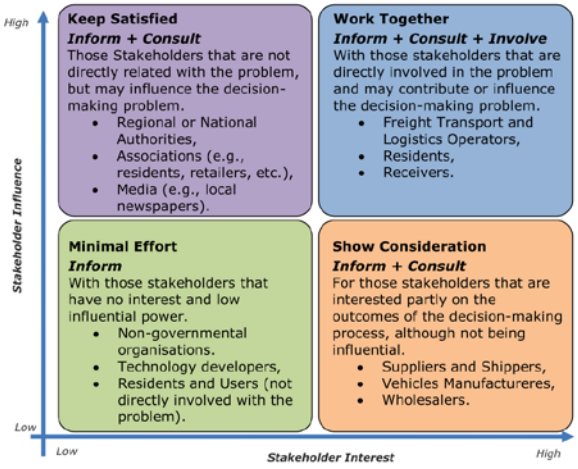


Figure 2. An Example of Stakeholder Classification Based on Influence and Interest
Source: van den Bossche et al. (2017, 16)

3. Stakeholder Engagement and Identification

A stakeholder analysis was conducted to satisfy the following research questions:

1) Who are the key stakeholders and what are their levels of influence and interest?
2) What is the public's perception of public transportation service?

3.1. Stakeholder Identification

Twenty-three stakeholders associated with the selected study network were identified. Using the categorisation as advocated by Kelly et al. (2004), these stakeholders were grouped into four main areas as shown in Table 1. The stakeholders listed were then positioned in a stakeholder matrix based on influence and, level of interest. Stakeholders were placed according to the definitions provided in the example quoted in Figure 2. Based on the classifications of van den Bossche et al. (2017, p.16), transport users were placed in the lower right quadrant of Figure 3. This is because transport users have a high interest and a low influence in transport network policy development. Analysis of user experiences and perceptions is critical in advocating to stakeholders with greater influence. Accordingly, this paper focuses on the activity patterns and the experience levels of transport users.

3.2 Stakeholder Engagement

Subsequent to the identification and classification of interest groups, the selection of an appropriate engagement technique is important for conducting a transport user survey. The European Commission has discussed some key considerations and guidelines for the selection of engagement techniques (van den Bossche et al., 2017). They include:

1) Considering a method which aligns with the available resources and timeframe allotted for the project or initiative.
2) Understanding the values and culture of the stakeholders considered.
3) Selecting a technique which permits the clear communication of key items to stakeholders and also provides an avenue for feedback.
4) Being open to innovative and alternative methods whilst recognising that in some cases traditional

Table 1. Port of Spain Transport Network Stakeholders

Stake-holder group	Code	Stakeholder Name
Govern-ment Level	G1	Traffic Management Branch, Ministry of Works and Transport (MOWT)
	G2	Ministry of Works and Transport (MOWT)
	G3	Ministry of Planning and Development
	G4	Port of Spain City Corporation
	G5	Trinidad and Tobago Police Service (TTPS)
	G6	Ministry of Social Development and Family Services
	G7	Ministry of Tourism
Operator Level	O1	Public Transport Service Corporation (PTSC) Taxi operators
	O2	Maxi-taxi operators
	O3	Water-taxi operator (National Infrastructure Development Company Limited (NIDCO))
	O4	Transportation Network Companies (TNCs) e.g., TTRideshare
	O5	
User	U1	Private transport users
	U2	Privately owned public transport users (e.g., maxi-taxi or taxi users)
	U3	Publicly owned public transport users (e.g., water taxi users, PTSC users)
	U4	The Consortium of Disability Organisations CODO)
	U5	Residents
	U6	Tourists
Business	B1	Downtown Owners & Merchants Association (DOMA)
	B2	Carpark and parkade owners and operators
	B3	Trinidad and Tobago Industry of Chamber and Commerce
	B4	Port Authority of Trinidad and Tobago
	B5	Media

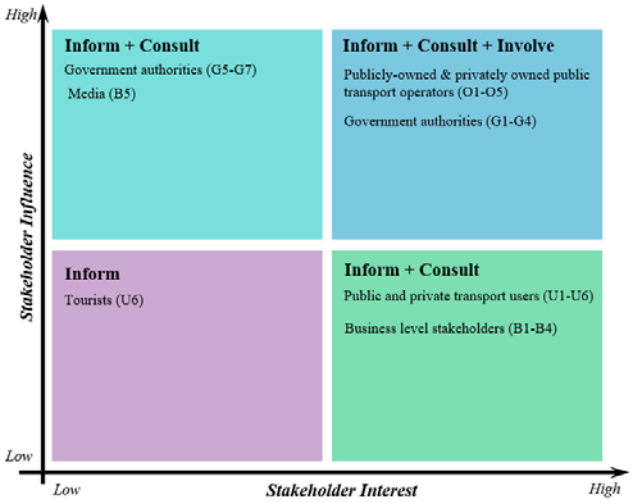


Figure 3. Classification of Port of Spain Transport Network Stakeholders

methods are most effective.

5) Considering engaging an expert or an individual who can manage any expectations and tensions.

Surveys, questionnaires, focus groups, interviews and meetings are some examples of traditional techniques which can be used to consult and collaborate with stakeholders (van den Bossche et al., 2017, p.23). Though researchers agree that stakeholder involvement increases the effectiveness and acceptability of transportation initiatives, stakeholder participation is commonly restricted to small groups. This issue is attributed to the planner's or researcher's inability to capture a large range of participants (Misra et al., 2014). To overcome limited participation Misra et al. (2014) encouraged embracing technology-mediated forms of engagement which do not rely on the physical presence of participants. Referencing multiple case studies, Misra et al. (2014) illustrated how traditional methods of data collection and feedback can be replaced to capture a wider group of participants without creating a financial burden. In 2018, an analysis of Trinidad and Tobago's digital landscape reported 0.8 million social media users and 1 million internet users (Kemp, 2018). This represents 58% of the population and 73% of the population, respectively. For this research, technology mediated forms were designed and distributed to encourage participation.

4. Methodology

A survey was undertaken to understand the travel patterns and experiences of the transport network users. A questionnaire containing nineteen questions was developed. It prompted participants to answer both quantitative and qualitative questions which focused on respondent demographics (such as, age, gender, disability), travel behaviour (such as, frequency of visits, the purpose of visit, journey origin, journey destination, modal preference, journey duration), monthly transport expenditure, and transport experience.

A non-random sampling technique was employed. The questionnaire was distributed on social media platforms and multiple open groups. Participants were encouraged to re-share the survey to expand the captured population sample groups. In total, two hundred and fifteen (215) responses were provided. Responses were accepted between 28th January, 2020, and 2nd March, 2020. This approach aligned with the time and financial resources available for the project and was expected to still produce results that were indicative of the commuting population.

4.1 Sample Description

Age and level of disability are socioeconomic characteristics that influence how the transportation system is experienced. Whilst other socioeconomic characteristics such as income may affect transportation choices, the reported experience is independent of those characteristics. Our current study did not collect income data. A recent household travel demand study of the East West Corridor showed that for a wide range of income levels, income had no significant effect on either trip generation or modal choice (Townsend, 2021).

From the two hundred and fifteen (215) responses obtained, 59% of survey participants were female and 41% were male. Age was divided into 8 categories which ranged from 17 years old to over 50 years old. Respondents predominantly fell within the 25 to 29-year-old age category. This was followed by the 30 to 34-year-old age category. The 17 to 19-year-old category was the least represented. Figure 4 shows the age distribution of the survey participants.

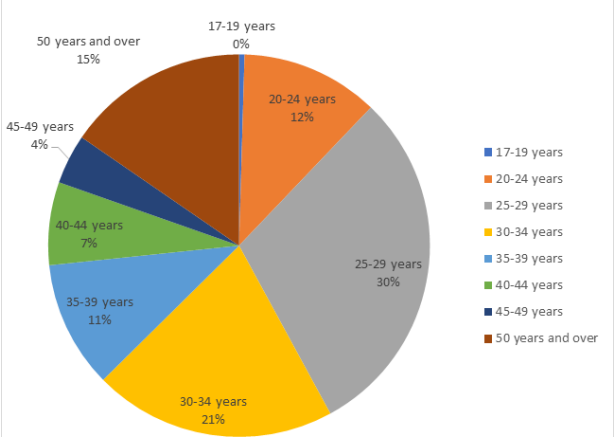


Figure 4. Age Distribution of Survey Respondents

Table 2 compares the sample age distribution to the 2011 Population and Housing Census (CSO 2012). As shown, there is an overrepresentation of 25 to 34-year-olds compared with 35 to 49-year-olds, indicating that the sample is skewed toward younger people within the 25 to 49-year-old generation. What this means is that the sample is more likely to have young single adults or married adults with no or young children.

Table 2. Comparison of Age Distribution

Age (years)	Population Percentage (%)	Sample Percentage (%)
20 – 24	14.7	12
25-34	29.4	51
35-49	35.3	22
Over 50	20.6	15

According to the World Health Organisation (WHO) disability is a broad term for impairment, activity limitations and participation restriction (WHO, 2002). Participants of the survey were prompted to indicate the presence of a long-standing disability. This was done to determine the experience of disabled groups.

As shown in Figure 5, 95% of respondents indicated 'No impairment', 4% highlighted the presence of a

'visual impairment' and less than 1% reported the presence of a 'physical impairment' and 'deaf/hard of hearing'. Comparatively, results from the 2011 Trinidad and Tobago Population and Housing Census indicated that there are approximately 52,244 individuals living with a disability (MSDFS, 2018). This represents 4% of the total population. Thus, the presence of disability within the sample appears to be at a similar level as the population.

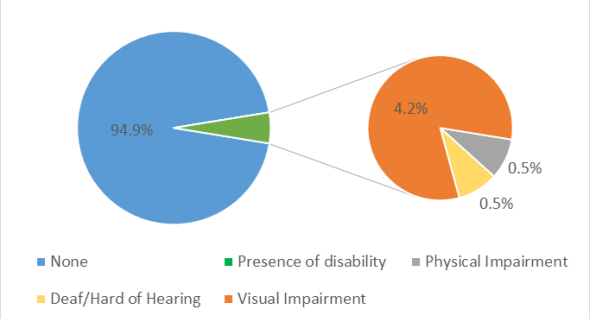


Figure 5. Disability Distribution

4.2 Journey Characteristics

The survey prompted participants to indicate the main purpose of their trips to Port of Spain. This was done to quantify the activity patterns of travellers (see Figure 6). The trip purpose categories considered were, (1) work; (2) business; (3) education; (4) shopping or leisure; (5) escort (for example accompanying children to school) and; (6) other.

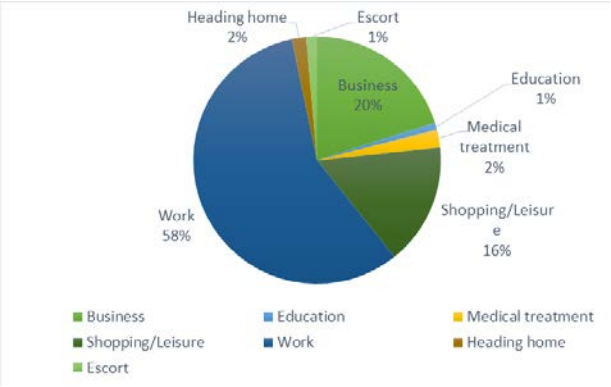


Figure 6. Reasons for Travelling into Port of Spain

Since Port of Spain functions as the centre of commerce and business in Trinidad and Tobago and houses the seat of government (Kairi Consultants Limited, 2016), it was expected that a large proportion of transport users enter the capital for business or work. Accordingly, considering the main trip purpose, fifty-eight per cent (58%) of respondents visited the city for work, twenty per cent (20%) for business and, sixteen per cent (16%) for shopping or leisure. The remaining six per cent (6%) contributed toward medical treatment, heading home and escort. Since the majority of the respondents indicated that their main purpose was "work", it is expected that timeliness is a critical factor to the majority of Port of Spain transport users.

4.3 Modal Choice Behaviour

In the context of transport engineering, a journey is defined as a one-way trip of travel which has a single purpose. A journey consists of one or more stages. For this research, a journey is separated into two main stages. The first stage is treated as a trip between the point of origin and entry point into Port of Spain. The second stage is considered as the trip from this entry point to the traveller's specified destination.

4.3.1 Modes Used to Arrive into Port of Spain

Figure 7 presents a non-exhaustive list of the motorised transport modes available to arrive in Port of Spain. As shown, public transport is disaggregated into publicly owned and privately owned.

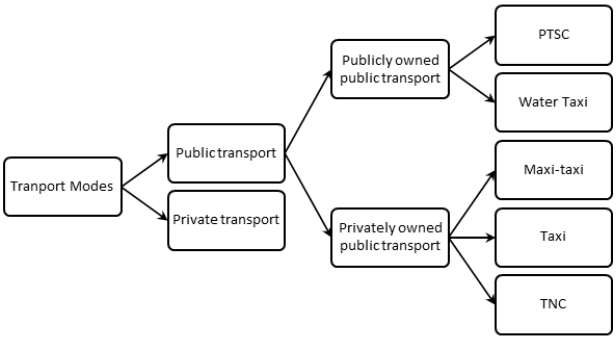


Figure 7. Available Transport Options for Entering Port of Spain

It was found that seventy-one percent (71%) of trips to Port of Spain are completed using private transport while approximately twenty-nine percent (29%) are made using public transport (see Figure 8). Maxi-taxi trips represent only nineteen percent (19%) of the sample population, the highest among public transport modes.

4.3.2 Modes used within Port of Spain

Figure 9 depicts the modal distribution of trips within the city. Forty-five percent (45%) of trips were completed using private vehicles whereas twenty-eight percent (28%) of trips were completed by walking. The distance between parking facilities and workplaces or business places accounts for the reduction in private car usage and increased use of walking during the second stage of journeys. Maxi-taxi usage within the capital contributed to only one percent (1%) of trips, a reduction of eighteen percent (18%) from the corresponding value reported (see Figure 8).

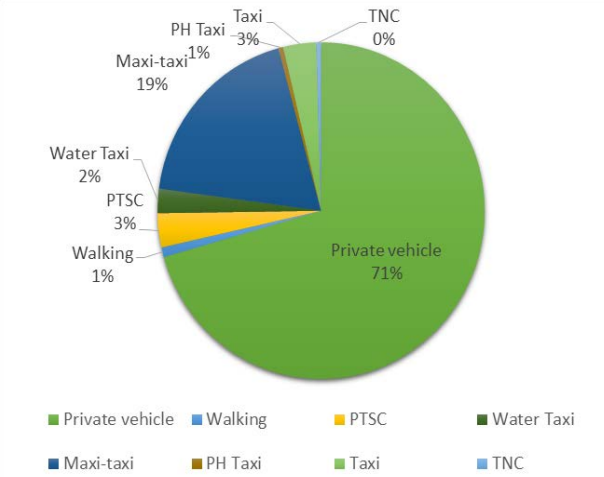


Figure 8. Distribution of Transport Mode used to Enter Port of Spain

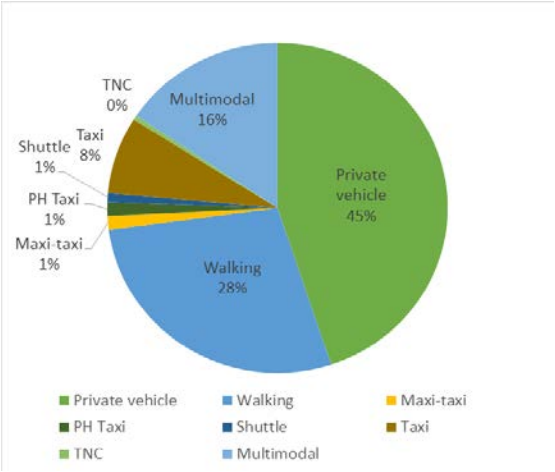


Figure 9. Distribution of Transport Modes within Port of Spain

The restricted maxi-taxi usage within the capital may explain this variation. It was found that sixteen percent (16%) of users indicated that the second stage of their journey may comprise of multiple modes of transport. Respondents reported using the following combinations of transport modes upon arrival in POS:

- Maxi-taxi, walking
- Private vehicle, walking
- Taxi, walking
- 'PH' taxi, taxi, walking
- Walking, taxi, TNC

The most popular multimodal combinations were (i) 'Maxi-taxi, walking' and (ii) 'Private vehicle, walking'. Figures 8 and 9 demonstrate the low usage of Transportation Network Companies (TNC).

4.4 Trip Purpose and Transport Mode

Adding another layer to this analysis, the relationship between trip purpose and transport mode was evaluated. A 100% stacked column chart was generated as shown in Figure 10. Except for homeward bound trips, private transport usage remained the predominant modal choice for each trip purpose considered. For trips to access education, medical treatment and to escort individuals, private transport was the only form of transport used. Thirty-three percent (33%) of trips into Port of Spain to get to work were facilitated using public transport, the highest public transport usage observed.

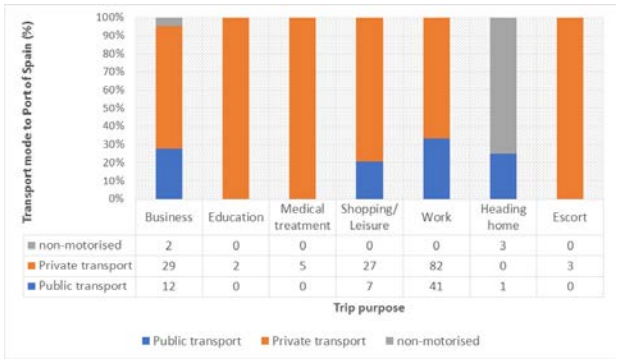
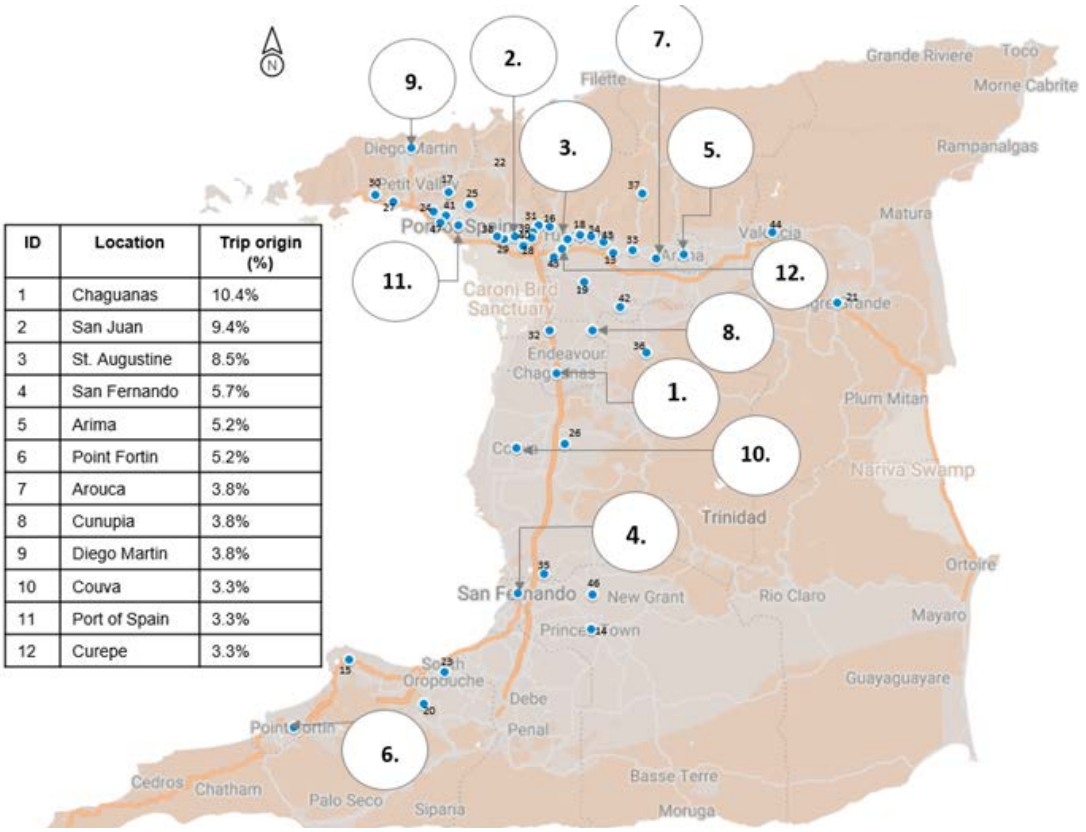


Figure 10. Relationship between travel activity and transport mode

Survey participants were prompted to indicate the start and endpoints of their trips. Using this data, the centroid road distance traversed by each participant was approximated using Google Maps. As demonstrated in Figure 11, trips originating from Chaguanas (10.4%) accounted for the highest percentage of trips recorded, followed by San Juan (9.4%) and, St. Augustine (8.5%). As shown in Figure 12, approximately forty-two per cent (42%) and seventeen per cent (17%) of trips ended within the Central Business District (also referred to as Downtown Port of Spain) and Woodbrook, respectively. These trends indicate that POS attracts travellers from throughout the country. Whilst under half of these trips end in Downtown POS, a significant portion of trips is dispersed in POS. This means that users may need to transfer or have a long walking trip within the city.

A bar chart was developed using the average distance travelled for each trip purpose (see Figure 13). The median distance travelled is 42km for medical treatment, 32km for business, 31.8km for shopping/leisure and 30.5km for work. There is a marginal difference between the distance travelled for business and work, however, the average distance travelled for healthcare is 31% greater than the average distance traversed for business. This suggests that, for the survey respondents, the distance patients are willing to journey to access healthcare is greater than the distance away from work. Related to this, (Kelly et al., 2016) revealed that factors excluding distance contribute to how easily patients are capable of travelling to access healthcare facilities. The results also indicate that POS is a unique destination for specialised medical care.



ID	Location	Trip origin (%)
1	Chaguanas	10.4%
2	San Juan	9.4%
3	St. Augustine	8.5%
4	San Fernando	5.7%
5	Arima	5.2%
6	Point Fortin	5.2%
7	Arouca	3.8%
8	Cunupia	3.8%
9	Diego Martin	3.8%
10	Couva	3.3%
11	Port of Spain	3.3%
12	Curepe	3.3%

Figure 11. Map Showing Trip Origins.

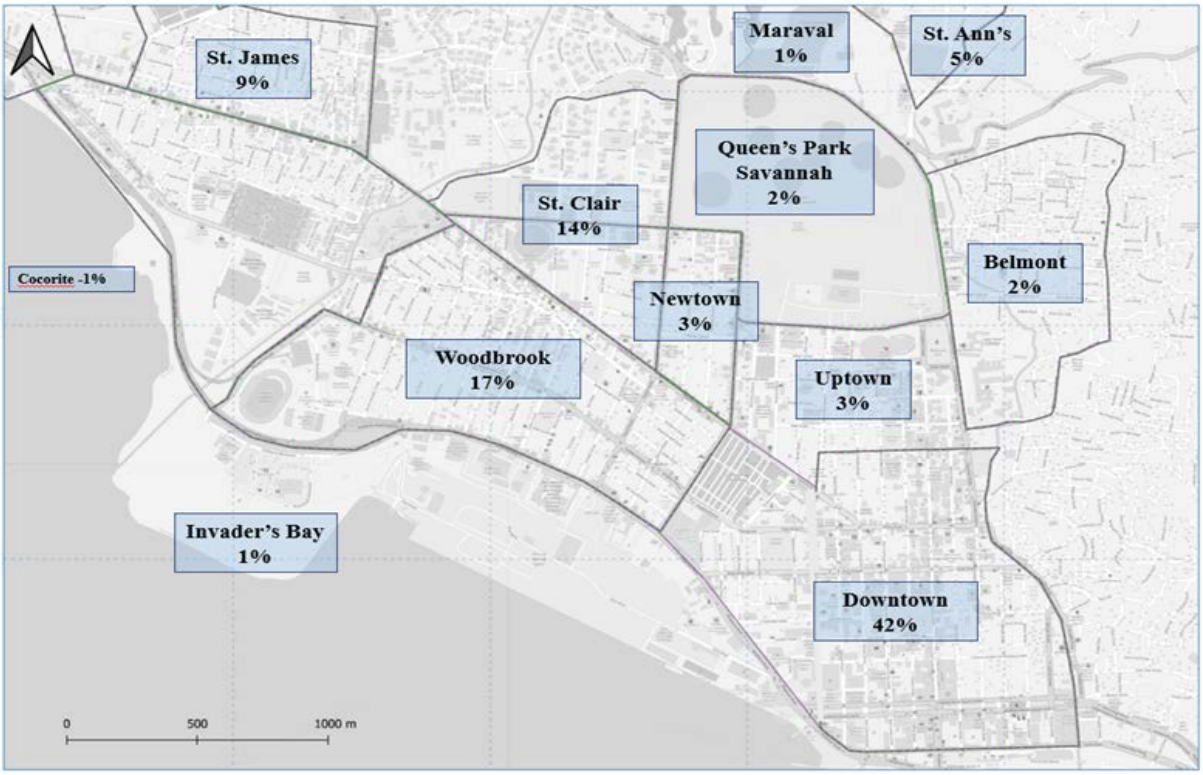


Figure 12. Map Showing Area of Interests upon Arrival in Port of Spain

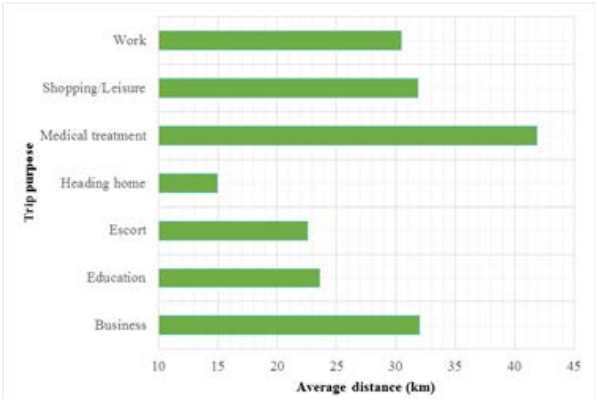


Figure 13. Average Travel Distance to Port of Spain Disaggregated into Trip Purpose

The monthly cost expended for transport was separated by public and private transport users. Private transport users reported an average monthly transport expense of seven hundred and thirty-three Trinidad and Tobago dollars ($733). Public transport users indicated a four hundred and sixty-six T&T dollars ($466) average monthly transport cost. This was almost two hundred and sixty-seven T&T dollars ($267) less than the corresponding private transport figure. The cost quoted for private transport users represents the fuel and parking costs whereas the prices quoted by public transport users signify the fares paid. The fuel cost and the public transport fare represent the 'out of pocket' direct user costs. Private transport cost did not include vehicle maintenance expenses, insurance fees and the cost of the vehicle. Similarly, public transport cost does not capture government subsidies. The results suggest that although private transport users report significantly higher costs, the advantages of using private transport outweigh using public transport.

4.5 Parking Choice Behaviour

During a telephone interview made on 21st March, 2012 with the Guardian Newspaper, the president of the Downtown Owners and Merchants Association (DOMA) underscored the symbiotic relationship between parking, vehicular access and the survival of downtown Port of Spain (Clyne, 2012). High private transport usage triggers high parking demands. Also, the quality of the available parking impacts traffic flow. According to (Furlonge, 2010), the rate of flow of traffic is related to how effectively both on and off-street parking can reintegrate vehicles into the system.

Figure 14 depicts the parking choice behaviour of survey participants. One-hundred and sixty-eight (168) participants indicated the use of either public parking lots, on-street parking or company parking provision. Of this, 46% of respondents utilise parkades or public paid parking lots, 20% use on-street parking and 35% benefit from company parking provision. Although the number of persons using parkades is significant, it is outweighed by the number of persons who park through company provision or on-street. This highlights that private transport users prefer to use a free parking option.

Figure 14. Parking Choice Behaviour

If a standard nineteen and a half square metres (19.5 sq.m) of land is allocated to provide parking for each private vehicle in the city (Garber and Hoel, 2002), ignoring multi-story carparking, approximately 430ha of space is required, 36% of the total area of Port of Spain. Leung (2009) reported data which suggested that 221,000 private vehicles entered Port of Spain each day. It is expected that private vehicle volumes have increased since then. Furthermore, these figures do not include the space required for vans, delivery vehicles, buses, trucks or taxis within the city.

4.6 Motor Fuel Choice

Fuel stations offer unleaded gasoline (for vehicles equipped with fuel-injected engines), compressed natural gas and diesel. The unleaded options include 'Super' which has an octane level of 92, and 'Premium' which has an octane level of 95. Hybrid vehicles are also available on the market having electrical energy capability. As shown in Figure 15, gasoline is the popular fuel choice for private transport users followed by diesel. Compressed Natural Gas (CNG) contributes to less than one percent of motor fuel usage. Dolcy (2019) argued

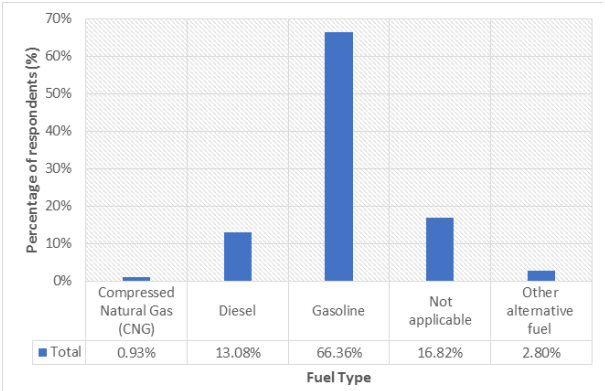


Figure 15. Motor Fuel Choice Based on a Commuter Survey

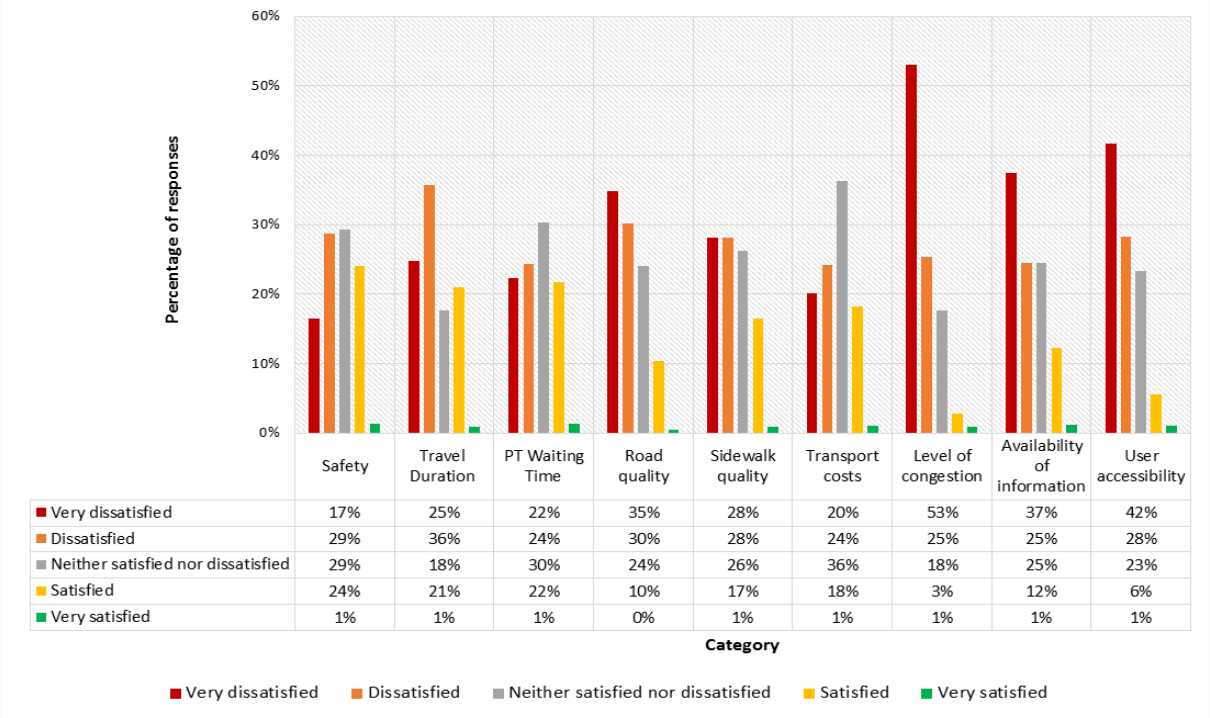


Figure 16. The Commuter Rating of Elements of the Port of Spain Transport Network

that the resistance toward CNG in private vehicles in Trinidad and Tobago is due to the cargo space required to accommodate fuel storage and the cost of conversion.

4.7 Commuter Satisfaction

Figure 16 shows the indicators used to measure the attitudes toward transport in Port of Spain. A 5-level Likert scale was used for the respondents to measure these indicators. The scale was categorised by: very satisfied, satisfied, neither satisfied nor dissatisfied, dissatisfied and very dissatisfied. Road quality, level of congestion, availability of information and user accessibility have a negative skewness, with most participants highlighting strong dissatisfaction with the level of service provided in these categories.

The highest percentage (53%) of respondents indicated strong dissatisfaction toward the congestion levels experienced. This was closely followed by user accessibility (42%), availability of information (37%) and road quality (35%). For transportation costs, the modal response was neutral (36%) however the combination of dissatisfied and very dissatisfied represents forty-four percent (44%) of the sample.

Fifty-six percent (56%) of respondents expressed dissatisfaction with the sidewalk quality. Since the analysis showed that walking is a part of most person's journey, the need to improve walking experience is critical.

'Safety' received an overall negative response with twenty-nine percent (29%) of respondents indicating dissatisfaction and seventeen percent (17%) stating strong dissatisfaction.

Compared to the other factors considered, safety received the least negative response. It should be noted that the definition of 'safety' was left to the respondents. No distinction was made between security, road safety or any other construct.

Figure 17 compares the perception of safety in POS based on gender. As shown, more females reported dissatisfaction with safety in POS compared to males. This trend substantiates the validity of the claims by Yáñez-Pagans et al. (2018) that women experienced more safety concerns when using transportation systems in Latin American and Caribbean cities.

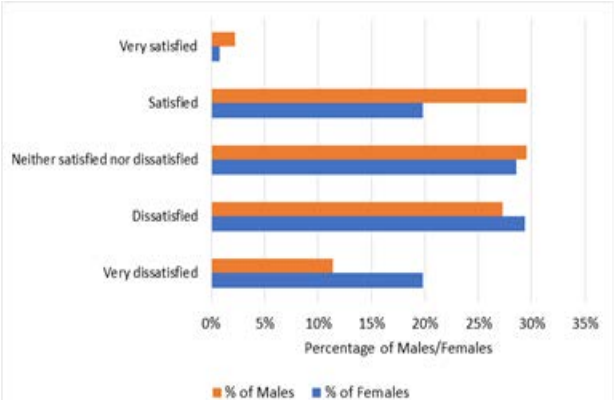


Figure 17. Rating of Safety Based on Gender

5. Conclusion

This paper examined the characteristics, preferences, and satisfaction of users of the Port of Spain (POS) transport network. The key stakeholders in the transportation network were identified and classified in a stakeholder matrix on the basis of their interest and influence. Four stakeholder groups were identified. These were government, operator, user and business.

A traveller survey was administered to gather information on traveler experience. Most survey participants travelled to POS for employment. On average, respondents travelled 31km to get to POS for work. Trips originate from several towns with the highest percentages from Chaguanas, San Juan and St. Augustine. The Central Business District (also referred to as Downtown Port of Spain) was the most popular destination followed by Woodbrook. Whilst under half of these trips end in Downtown POS, a significant portion of trips were destined for areas other than the Central Business District. This means that commuters, especially public transportation users need good intra-city connections and easy walkability to destinations in order to complete their journeys.

Private vehicles continue to be the dominant transport mode choice. The analysis of the travel mode used to enter POS showed that 71% of trips were completed using private transport. The remaining 29% used public transport. Although only 19% of the trips were completed by maxi-taxis, this mode was the most popular public transport used to enter POS. A significant disparity between public transport and private transport direct user costs was observed. Specifically, private transport users reported an average monthly transport cost of $733 Trinidad and Tobago dollars compared to $466 Trinidad and Tobago dollars reported by public transport users. These trends indicate that although private transport users report significantly higher costs, the advantages of using private transport outweigh using public transport.

Transport users who participated in the survey were broadly dissatisfied with the system. Although the 'safety' category received the least negative response, approximately 46% of respondents were dissatisfied or very dissatisfied.

Participants indicated strong dissatisfaction with the congestion experienced in the capital city. Whilst the modal response for transport cost was neutral, the combined number of persons indicating either dissatisfied or very dissatisfied was higher than those who were neutral. Apart from congestion, commuters were very dissatisfied with both accessibility and the availability of information. This problem would be particularly acute for public transport users who need to transfer from one vehicle to another.

Transport safety received the least negative responses among the transport indicators examined. Also, in general females reported more dissatisfaction with transport safety compared to men. For every measured aspect of the transport system, more people were dissatisfied than either satisfied or neutral. A minimum of forty-four percent (44%) and a maximum of seventy-eight percent (78%) of respondents were either dissatisfied or very dissatisfied with some aspects of the transport system. No more than twenty-five percent (25%), and the case of congestion only three percent (3%), of respondents were either satisfied or very satisfied.

The research points to the need to take actions that would improve the travel experience of public transportation users both into and around the city. These actions should include improving their access to information about public transportation services so that they can have more confidence in using these services to fulfill their travel requirements and conditions.

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Production and Characterisation of a Novel Dasheen (*Colocasia esculenta*) Alcoholic Fermented Beverage

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Abstract: *In this study, an alcoholic fermented beverage of acceptable quality characteristics was produced from two types of dasheen (Colocasia esculenta L. Schott) musts, A – boiled dasheen must and B – cooked dasheen with must, each at three total soluble solids (TSS) levels (18, 22 and 25 ˚Brix). Quality characteristics of pH, TSS, alcohol content, titratable acidity (TA), specific gravity (SG), and spectrophotometric, microbiological, and sensory evaluations were analysed in the fermented beverages. Fermentation caused pH, SG and TSS to decrease while simultaneously increased TA. Coliforms were not detected in any of the must and fermented beverage samples. The one-way ANOVA showed a significant difference ($p<0.05$) when the fermented beverage from musts A and B was compared on the final quality parameters of pH, SG, TSS, TA, a* component and sensory attributes (appearance, colour, taste, and mouthfeel). The beverage made from batch A, 25 ˚Brix was consumer acceptable based on sensory and physicochemical analyses with a pH of 3.12, SG of 1.0053, TSS of 10.13 ˚Brix, TA (% citric acid) of 0.75% and an alcohol content of 14.00 and 12.52% using the hydrometer and gas chromatography methods respectively. For the spectrophotometric analysis, the absorbance at 420 nm wavelength was 0.246 while the L* a* b* colour indices were 88.59, 0.13, and 1.36 respectively. The overall results indicate that this product can be beneficial to the Caribbean food and beverage industries.*

Keywords: *Dasheen (Colocasia esculenta), alcoholic fermentation, sensory attributes, colorimetry, spectrophotometry, gas chromatography-flame ionisation detector*

1. Introduction

Colocasia esculenta L. Schott commonly known as taro or dasheen is a tropical crop that belongs to the Araceae family or *Arum* genus (Deo et al., 2009). Dasheen production occurs yearly in many parts of the world, including Asia, Pacific, Africa, and the Caribbean (Ramantha Rao et al., 2010). However, the corms have a high moisture content, which can decrease its shelf life and contribute to spoilage, leading to significant postharvest wastage of the crop (Deo et al., 2009; Himeda et al., 2014). Fermented beverages from taro are generally unknown globally, however a recent study was reported on kefir-fermented beverage from the extract of *C. esculenta* with a shelf life of 21 days (Pinto et al., 2021). Alcoholic fermentation of the dasheen corm can increase its shelf life and add value to the product which can have immense economic and food security benefits.

Globally, there is a dearth of scientific reports on consumer acceptability and quality characteristics including physicochemical properties of fermented taro alcoholic beverages. Fiscal and Chavez (2016), produced a fermented alcoholic beverage from taro corms, but enhanced its flavor by the addition of calamansi (*Citrofortunella microcarpa*), santol (*Sandorium koetjape*), and dalanghita (*Citrus nobilis)* in the fermentation wort. The study revealed that the yeast quantity, fermentation temperature and duration, affected the pH while the fermentation temperature and duration, affected the alcohol and the total soluble solids content of the beverage. Another scientific report focused on ethanol production from dasheen or cocoyam fermentation, converting the starchy root crop into a fermentable sugar (wort) by a two-stage enzyme hydrolysis process (Braide and Nwaoguikpe, 2011).

In Trinidad and Tobago, homemade fermented alcoholic beverages are produced from dasheen corm as a by-product utilising the residue after boiling dasheen for consumption. The product has tremendous potential for commercial production, however, research and development is required to ensure consumer acceptability and quality standardisation of an acceptable product is achieved. This research is aimed to produce a fermented dasheen beverage that is acceptable to consumers through sensory evaluation and determine the physicochemical

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and microbial parameters required to maintain quality standards during commercial production.

The fermented beverages from the must of two batches were evaluated i.e. A-the must only from the strained cooked dasheen and B-the cooked dasheen with the must, at three total soluble solids levels of 18, 22 and 25 ˚Brix. Microbiological analyses were conducted throughout the fermentation process (from raw material to final product). Physicochemical parameters (pH, specific gravity, total soluble solids, titratable acidity) were evaluated during primary fermentation and at the finished product stage. Gas chromatography/Flame Ionisation Detection (GC/FID), spectrophotometry, colorimetry, microbiology, and physicochemical parameters of the final products were evaluated and compared to a commercial Dasheen alcoholic beverage manufactured in Tobago. After a ranking method confirmed the preferred sugar concentration, a sensory evaluation was conducted on the final products made from musts A and B to determine overall consumer acceptability.

2. Methods

2.1 Preparation of the Dasheen Must

Freshly harvested unbruised dasheen corms (*Colocasia esculenta* L. Schott) were washed, hand peeled and sliced into 6.0 mm rectangular wedges using a meat slicer (Hobart Model 1612). After washing and draining the wedges, a batch weighing 1.2 kg was boiled until cooked (15 min) in a sterilised stainless-steel pot containing 4.5 L of clean potable water. The mixture was then cooled to 37 ˚C and strained into an 8 L bucket to remove the dasheen from the water and dasheen must (Must A). For Must B, the mixture was not strained, and the dasheen was added to the 8 L bucket. At 37 ˚C, 0.29 g of the enzyme amylase (LD Carlson, OH, USA) was added. Then, the pH was reduced to 3.5 by adding a 50:50 (v/v) citric acid (Sigma Aldrich, Canada) solution. Granulated sugar (155.56 g L^{-1}) was used to increase the TSS to 18 ˚Brix. Yeast nutrients, 0.99 g L^{-1} of ammonium sulphate (SD Fine – Chem Limited, Mumbai, India) and 0.99 g L^{-1} of monobasic ammonium phosphate (Fisher Scientific, New Jersey, USA) were also added to the dasheen mixture.

To prevent proliferation of wild microorganisms, 0.14 g L^{-1} of sodium metabisulphite (HiMedia, Mumbai, India), (SMS) was added. Feiner (2006) noted that the sodium dioxide equivalent was 67% of the sodium metabisulphite added, which is lower (93.8 ppm) than the maximum permissible limit (100 ppm) prescribed in the Food and Drugs Act, Chapter 30:01 (Government of the Republic of Trinidad and Tobago (GORTT), 2022). The solution was covered and after 24 h, 1.11 g L^{-1} of dehydrated yeast, (Lalvin EC - 118 *Saccharomyces cerevisiae ex bayanus*) was added to the 4.5 L dasheen must batch. After 10 min, 15 mL of the pre-SMS and post-SMS yeast musts were collected for microbiological analysis. The solution was then allowed to undergo primary and secondary fermentation, pasteurisation and finally bottling.

The above process was repeated for Must A using 255.56 g L^{-1} and 277.78 g L^{-1} granulated sugar to increase the TSS to 22 and 25 ˚Brix respectively as illustrated in Figure 1. All other variables were held constant. Similarly, these steps were repeated for Must B resulting in six batches (3 sugar concentrations x 2 musts).

2.2 Preparation of Fermented Alcoholic Dasheen Beverage

The musts (A and B) for each sugar concentration (18, 22 and 25 ˚Brix) were fermented at 28 ˚C (monitored daily) for 7 days in 8 L buckets. Before pitching the yeast (1.11 g L^{-1}), the solution was stirred very well. On day 1 after yeasts addition (10^7 cfu mL^{-1}) to the musts, pH, total soluble solids (TSS), specific gravity (SG) and the titratable acidity (TA) measurements were taken. These parameters were measured daily for 7 days, to monitor the primary fermentation process, while on day 7, the alcohol content was measured. Racking involved siphoning the musts (A and B) from each sugar concentration into 4.5 L sanitised, glass carboys, leaving sediments in the 8 L buckets after 7 and 21 days respectively. Fermentation locks half-filled with distilled water were used to cover the mouth of the carboys for each racking. A third racking of the musts was done 21 days after the second racking. One week after the third racking, the six dasheen batches were pasteurised for 15 min at 60 ˚C by using a sterilised stainless-steel pot on a mild flame equipped with a digital thermometer (Thermo Works RT610B-24). A 15 mL sample of the musts from each racking and each batch were taken for microbiological analysis. The batches were cooled at 30 ˚C for 25 min and then transferred to pre-sterilised 750 mL glass bottles for further analyses.

2.3 Microbiological Analysis

Microbiological analysis was done to monitor the fermentation process, prevent microbial spoilage of the musts and ensure safety of the finished product (International Organisation of Vine and Wine (OIV), 2021). Plate count Agar (PCA), Dichloran Rose Bengal Chloramphenicol (DRBC) and Violet Red Bile Agar (VRBA) (Oxoid Limited, Hampshire, UK) were used to enumerate the total aerobic bacteria, yeasts and molds, and coliforms, respectively. The Butterfield's Phosphate-buffered dilution water (10 g sample in 90 mL diluent) was used to serially dilute the raw dasheen, musts, and final samples (Harrigan, 1998). Serial dilutions for the musts Pre-SMS (10^0 to 10^{-4}), Post-SMS (10^0 to 10^{-3}) and after the addition of yeasts (10^{-2} to 10^{-6}) were prepared while similar dilutions were prepared for each racking and for the final and commercial alcoholic beverages. The total aerobic bacteria, yeasts and molds and coliforms (cfu mL^{-1}) were calculated using the colony counter (Reichert, Model No: 3325, USA).

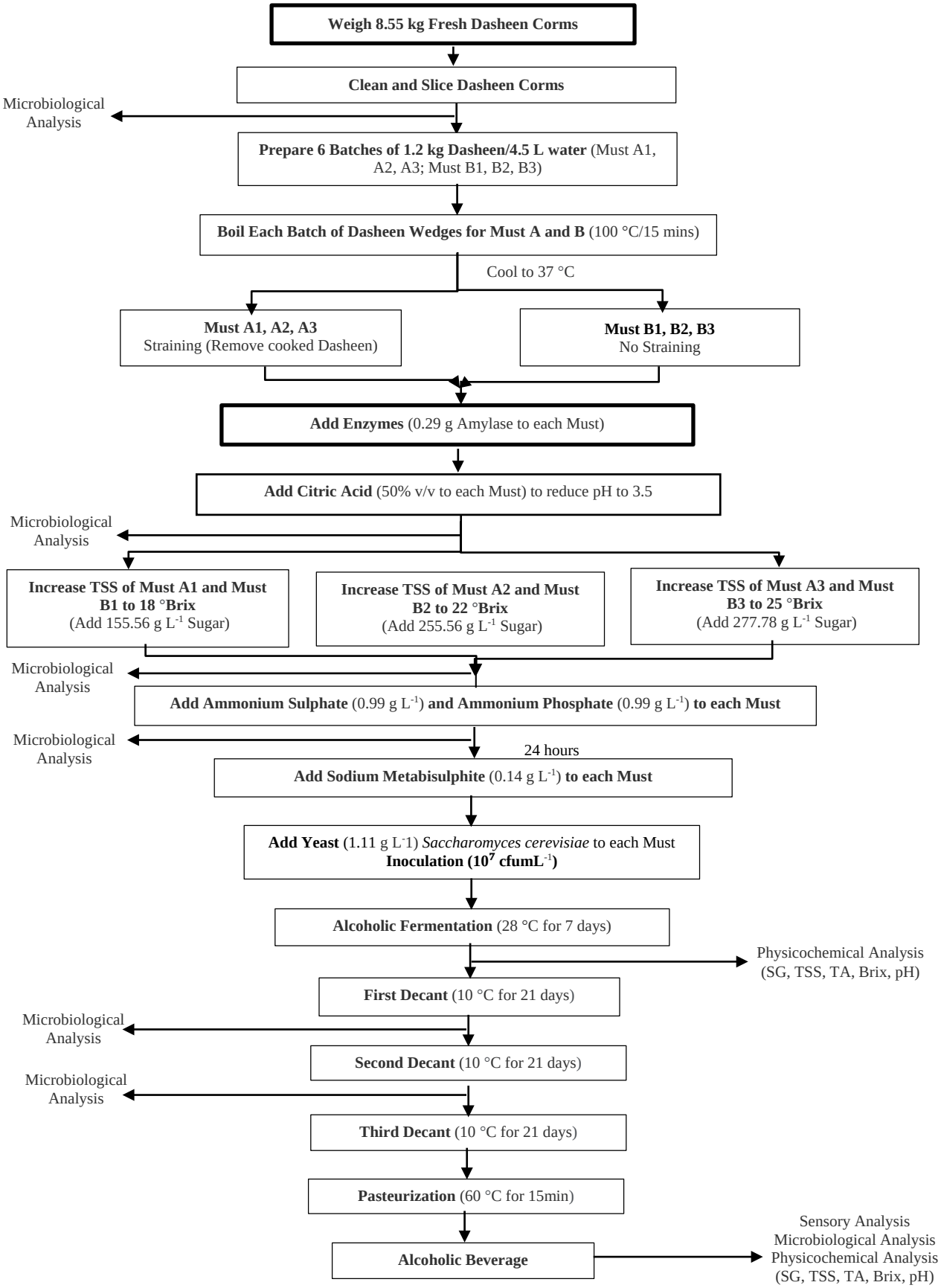

Figure 1. Process Flow Diagram and Microbiological Analysis for Preparation of Dasheen Alcoholic Beverage by Controlled Fermentation

2.4 Physicochemical Analysis

For the dasheen musts and fermented alcoholic beverages, the pH, specific gravity (SG), total soluble solids (TSS), titratable acidity (TA), and the alcohol content were determined using the analytical methods of the wine industry (Horwitz and Latimer, 2005; Ough and Amerine, 1988). The pH of the fermenting musts and the final products were monitored using a portable digital pH meter (Oakton Instruments 150, IL, USA). For the SG and potential alcohol content, a triple scale hydrometer (1983 EH 89 BT Ellaway Glass, Edinburgh, UK) with two scales was used to measure both the SG and the potential alcohol content (Jacobson, 2006). The TSS (˚Brix) was measured using a refractometer (Reichert, Analytical Instruments - 1452/62216/065). The TA was measured by the titration method with 0.1 N sodium hydroxide as the base and expressed as % citric acid (Jacobson, 2006).

2.5 Ethanol Concentration Analysis

The ethanol concentration of the fermented dasheen beverages was compared to that of a commercial dasheen fermented beverage using the gas chromatography method (Stackler and Christensen, 1974; Buckee and Mundy, 1993). An Agilent Technology (model 7890-A) GC system interfaced to an injector (7683-B series injector) with a Flame Ionised Detector (FID) at 250 ˚C was used to achieve chromatographic separation using 0.2 µL samples from 8 mL each of the commercial and the final fermented alcoholic beverages which were centrifuged (IEC Centra, USA model - CL4), at 6000 rpm for 15 min. The identification of the alcohol compounds was carried out by comparing their retention times with those of standards using a 5% propan-2-ol internal and ethanol standards (5%, 7.5%, 10%, 12.5%, 15%). The ethanol concentration mixtures were inserted into the GC storage sampler, followed by the final fermented product and commercial product mixtures. Two peaks were observed on each chromatogram, ethanol (longer peak) and propan-2-ol (shorter peak) and based on the retention times, peak areas quantified, and the alcohol content obtained (Stackler and Christensen, 1974).

2.6 Colour Analysis

A Thermo Scientific Evolution 60 s UV-Visible Spectrophotometer was used to determine the absorbance (A) of the finished products at 420 nm in triplicate (Blesic et al., 2013), while a Chroma meter (CR – 410, Konica Minolta Sensing, Inc; Ramsey, NJ, USA) was used to determine the Hunter values (L*, a*, b*) of the final and commercial products (Pathare et al., 2012).

2.7 Sensory Evaluation

The preferred sugar concentration was determined using a Preference Ranking Test to evaluate the samples, and these are ranked in order of preference. The three (3) samples from Must A were coded differently with 3-digit numbers and served to semi-trained individuals in a sensory evaluation booth. Respondents were required to indicate their preference for each product in the order from most liked sweetness (1) to moderately liked sweetness (2) to least liked sweetness (3) on a survey sheet provided. This procedure was repeated for the three (3) samples from Must B. Sensory evaluation of the final products made from the preferred sugar concentration for musts A (boiled dasheen must) and B (cooked dasheen and must) was then used to determine consumer acceptability and to evaluate whether the beverages from must A and B were discernable from each other.

The process involved training 30 panelists in sensory evaluation techniques including reducing biases and to distinguish the main characteristics of the beverage (Kilcast, 2000). The 30 semi-trained panelists were used to determine consumer acceptability by blind sampling and rating of the sensory attributes (appearance, colour, aroma, taste, and mouthfeel) of the beverage using a 5 – point hedonic scale from I like extremely (1), I like slightly (2), I neither like nor dislike (3), I dislike slightly (4) to I dislike extremely (5) (Fiscal and Chavez, 2016). A triangle test was used to determine whether there was a difference in the fermented beverage from Must A and Must B. In this test, respondents were asked to determine the odd sample from three (3) samples, where one sample was repeated twice (Hartley et al., 2022).

2.8 Statistical Analysis

All experiments were carried out in triplicate and the results expressed as the mean $\pm$ SD. The results were subjected to a one-way analysis of variance (ANOVA) using the IBM SPSS Statistics Data Editor (SPSS Inc., Chicago, IL, USA). Significant differences were established at the $p<0.05$ level.

3. Results and Discussion

3.1 Microbial Analysis of Musts and Fermented Beverages

Table 1 shows the microbial count throughout the fermentation of dasheen for both must types (A and B) and at the three TSS levels. The population of aerobic bacteria, yeasts and molds in raw ‘uncooked’ dasheen were 1.39 x 10^8, 2.1 x 10^8 and 29 cfu mL^{-1}, respectively. Generally, the microorganisms present on the raw dasheen samples allowed for the natural fermentation process to occur (Pambianchi, 1999). In the Pre-SMS stage, the microbial population decreased, as the dasheen was boiled in hot water. The B must, had a greater yield of aerobic bacteria than the A must, as it included the cooked dasheen wedges in the must. In the Post-SMS stage, the microbial population drastically declined, and this step was very crucial, to kill unwanted, bacteria and yeasts present in the original samples which could have contributed to unpalatable flavours. After inoculation of the must with the commercial wine yeast, primary fermentation commenced. Initially, it appeared that the yeast adapted to the new environment prior to cell division while

Table 1. Microbial Count of the Raw Dasheen and Must A and B during the Fermentation Process at 18, 22 and 25 °Brix

SAMPLE	TOTAL AEROBIC BACTERIA			YEASTS			MOLDS			COLIFORMS		
°BRIX	**18**	**22**	**25**	**18**	**22**	**25**	**18**	**22**	**25**	**18**	**22**	**25**
Mean values (cfu mL^{-1})												
Raw Dasheen	1.39×10^8	1.39×10^8	1.39×10^8	2.1×10^8	2.1×10^8	2.1×10^8	29	29	29	0	0	0
PRE-SMS												
A	1.26×10^7	1.17×10^7	1.05×10^7	1.61×10^7	1.79×10^7	1.93×10^7	21	15	9	0	0	0
B	1.35×10^7	1.28×10^7	1.13×10^7	1.72×10^7	1.85×10^7	2.07×10^7	38	22	13	0	0	0
POST-SMS												
A	12	10	6	32	25	13	3	1	3	0	0	0
B	21	14	10	41	34	21	10	2	4	0	0	0
MUST AFTER YEASTS ADDITION												
A	1.43×10^6	1.32×10^6	1.22×10^6	1.29×10^7	1.41×10^7	1.67×10^7	5	2	4	0	0	0
B	1.51×10^6	1.39×10^6	1.41×10^6	1.34×10^7	1.53×10^7	1.75×10^7	16	12	6	0	0	0
FIRST RACKING												
A	1.18×10^5	1.06×10^5	9.60×10^5	1.09×10^6	1.23×10^6	1.45×10^6	2	1	2	0	0	0
B	1.30×10^5	1.17×10^5	1.09×10^5	1.20×10^6	1.39×10^6	1.58×10^6	9	7	3	0	0	0
SECOND RACKING												
A	8.70×10^4	7.80×10^4	6.90×10^4	7.90×10^4	8.70×10^4	9.60×10^4	0	0	0	0	0	0
B	1.03×10^4	9.20×10^4	7.50×10^4	8.60×10^4	9.40×10^4	1.05×10^4	5	3	0	0	0	0
THIRD RACKING												
A	4.40×10^3	3.10×10^3	2.70×10^3	3.20×10^4	4.50×10^4	5.70×10^4	0	0	0	0	0	0
B	6.70×10^3	4.60×10^3	3.40×10^3	4.10×10^4	5.30×10^4	6.20×10^4	0	0	0	0	0	0
FINAL RACKING												
A	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0	0	0	0	0
COMMERCIAL WINE												
	2	2	2	0	0	0	0	0	0	0	0	0

simultaneously converting sugar to alcohol as described by Nobile et al. (2003). This process lasted for 7 days, whereby excessive amounts of energy were consumed as heat, oxygen, and increased temperature. Additionally, carbon dioxide (CO_2) was expelled through the bung, and this led to the rapid growth of yeast cells (exponential phase) (Braide and Nwaoguikpe, 2011).

After primary fermentation, the product was racked (secondary fermentation) and the microbial population continued to decline as shown in Table 1. During this stage, the rate of yeast multiplication declined since there were limited nutrients (sugars) for it to consume and the alcohol produced was toxic for yeast proliferation (Braide and Nwaoguikpe, 2011). A temperature decrease was noted since the energy produced was released by the fermentation tank (carboy) into the surroundings. The remainder of alcohol was produced at the secondary stage, which lasted between 7 to 14 days and the death rate of microbes was higher than the proliferation rate (Nobile et al., 2003). From the second into the third racking, most of the microbial population was killed and a few survivors (survival phase) probably remained. The final fermented alcoholic beverage was carefully pasteurised to destroy any remaining microorganisms, and to preserve its aroma and flavour. Coliforms were not detected in any of the must and fermented alcoholic samples as illustrated in Table 1.

3.2 Physicochemical Analysis of Musts and Fermented Beverages

During primary fermentation there was a general decline in the pH, SG and TSS while the TA (% citric acid) increased as shown in Figure 2, for the preferred 25 ˚Brix from must A and this trend was like reported studies (Braide and Nwaoguikpe, 2011; Ifie et al., 2012; Kiin-Kabari et al., 2019). Generally, the primary fermentation stage was characterised by a high fermentation rate, due to the available yeast nutrients at the start of the process and production and accumulation of organic acids (Nobile et al., 2003; Kiin-Kabari et al., 2019) while in the secondary stage, the fermentation rate slowed down because of alcohol concentration on yeast cells (Braide and Nwaoguikpe, 2011).

The initial pH decline during primary fermentation was indicative of a relatively good fermentation rate due to sugar utilisation by the yeast cells (Braide and Nwaoguikpe, 2011; Nobile et al., 2003) in an acidic medium. It demonstrated the yeast efficiency in alcohol production (Nobile et al., 2003; Ifie et al., 2012) which also caused the SG to decrease as illustrated in Figure 2 like previous studies (Braide and Nwaoguikpe, 2011; Nobile et al., 2003; Chilaka et al., 2010; Kiin-Kabari et al., 2019). Low pH and high acidity gave fermentation yeast a comparative advantage in natural acidic environments which inhibited spoilage microorganisms and created a favourable environment for the growth of desired organisms (Braide and Nwaoguikpe, 2011; Kiin-Kabari et al., 2019). The TSS declined during primary fermentation (see Figure 2) as the yeast consumed the sugars present in the must, producing ethanol and CO_2

which resulted in a decrease in SG (Ifie et al., 2012; Chilaka et al., 2010). The 25 ˚Brix A must had highest TSS levels during primary fermentation compared to the other must and sugar concentrations as noted in Figure 3.

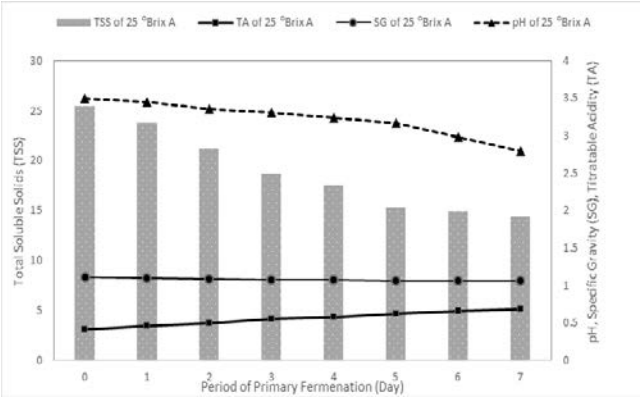

Figure 2. Changes in Quality Parameters during Week 1 of Primary Fermentation of Dasheen

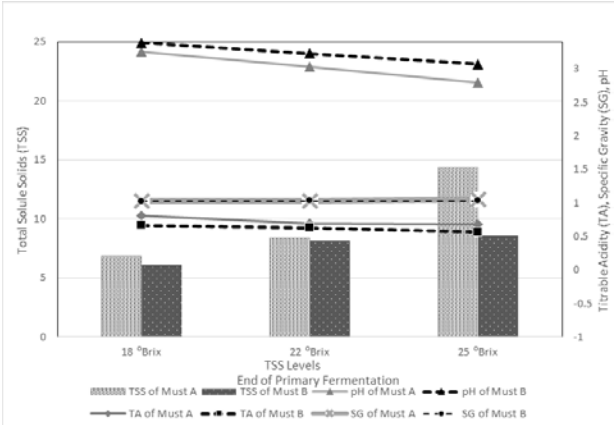

Figure 3. Quality Parameters of the Dasheen Musts for the Three TSS Levels at the end of Primary Fermentation

The TA (% citric acid) increased during primary fermentation (see Figure 2) and is like previous studies for pawpaw must, where an acidic medium encouraged optimum yeast activities resulting in organic acids accumulation during fermentation (Kiin-Kabari et al., 2019).

Table 2 shows the pH, SG, TSS and % citric acid data for the fermented dasheen alcoholic beverage from musts A and B for the three TSS levels (18, 22 and 25 ˚Brix). The type of must treatment significantly affected ($p<0.05$) the pH, SG, TSS and TA. An acidic pH was observed for all the six fermented alcoholic beverages, with the must A exhibiting a lower pH than the B must at the three TSS levels. Components that resulted in reducing the pH included esters, CO_2, phenolic compounds, and organic acids (lactic acid and acetic acid) via metabolic actions (Chilaka et al., 2010; Kiin-Kabari et al., 2019). The 25 ˚Brix A product was favoured with a pH of 3.12 which was within the pH range of 2.80 to 3.33 for alcoholic beverages (Fiscal and Chavez, 2016; Ifie et al., 2012) and was significantly lower ($p<0.05$) than the commercial fermented alcoholic beverage as noted in Table 6.

The final products SG ranged from 0.9933 to 1.0053 as shown in Table 2. Upon completion of fermentation, the SG was below 1.000 for the various ˚Brix concentrations and treatments (A and B) except for the 25 ˚Brix A and commercial wines probably because of their high TSS. The SG of the 25 ˚Brix A product averaged 1.0053 and was significantly lower ($p<0.05$) than the commercial product (see Table 6) as the density was increased by fermentable sugars and other substances (Ifie et al., 2012; Chilaka et al., 2010).

The final product TSS varied from 4.37 for the 18 ˚Brix B to 10.13 for the 25 ˚Brix A fermented products (see Table 2). The TSS for the 25 ˚Brix A fermented product, was significantly higher ($p<0.05$) than the B one but was significantly lower ($p<0.001$) than the commercial sample. The high TSS for the 25 ˚Brix A product was probably due to incomplete consumption of sugars by the yeasts during fermentation resulting in a semi – dry alcoholic beverage. The fermentation rate was slower, or probably ended earlier for this product compared to the commercial one which most probably was back sweetened.

Table 2. Physicochemical Analysis of the Final Fermented Alcoholic Beverages Produced from the Dasheen Must

Parameters	18 ˚Brix		22 ˚Brix		25 ˚Brix		*P*-value
	A	B	A	B	A	B	
pH	3.11 ± 0.06^{a}	3.42 ± 0.06^{b}	2.89 ± 0.06^{a}	3.10 ± 0.06^{b}	3.12 ± 0.06^{a}	3.34 ± 0.06^{b}	.001
SG	0.9973 ± 0.0012^{b}	0.9973 ± 0.0012^{b}	0.9993 ± 0.0012^{a}	0.9973 ± 0.0012^{a}	1.0053 ± 0.0012^{a}	0.9933 ± 0.0012^{b}	.005
TSS (˚Brix)	5.07 ± 0.06^{c}	4.37 ± 0.06^{c}	6.17 ± 0.06^{c}	6.27 ± 0.06^{c}	10.13 ± 0.06^{d}	6.57 ± 0.06^{c}	.009
TA (% citric acid)	0.86 ± 0.04^{f}	0.72 ± 0.00^{g}	0.75 ± 0.01^{f}	0.69 ± 0.00^{g}	0.75 ± 0.00^{f}	0.63 ± 0.00^{g}	.001
% Alcohol (hydrometer)	11.01 ± 0.19^{h}	9.92 ± 0.19^{h}	13.18 ± 0.19^{h}	12.64 ± 0.19^{h}	14.00 ± 0.19^{h}	13.72 ± 0.19^{h}	.504
% Ethanol (GC)	8.87 ± 0.02^{i}	8.59 ± 0.00^{i}	12.00 ± 0.00^{i}	10.81 ± 0.00^{i}	12.52 ± 0.01^{i}	12.36 ± 0.01^{i}	.599

Values are means ± SD for n=3; values within same row with different superscript differ significantly ($p<0.05$)

The TA of the final fermented products ranged from 0.63% to 0.86% as shown in Table 2 falling within reported levels of 0.38 to 1% (Chilaka et al., 2010; Kiin-Kabari et al., 2019) with the must A treatment TA significantly higher ($p<0.05$) than the B one. The 25 ˚Brix A finished product TA value of 0.75% was significantly higher ($p<0.05$) than the 0.22% for the commercial product.

3.3 Alcohol Content of Fermented Beverages from Gas Chromatography (GC) and Hydrometer Methods

The ratios of ethanol to propan-2-ol peak area in Table 3 were calculated for the commercial and final fermented samples and the alcohol content was interpolated from a linear graph of the mean ratio of the ethanol/propan-2-ol peak area of the standards against ethanol concentrations obtained from GC analysis. The first peak observed on the chromatogram was ethanol while the second peak was propan-2-ol, as shown in Figures 4 and 5 for the 25 ˚Brix A and B fermented products respectively.

Table 3. Ratios of the Ethanol to Propan-2-ol Peak Areas of the Commercial and Final Dasheen Alcoholic Beverages

Type of sample (˚Brix)	Ratio of Ethanol/Propan-2-ol (Mean ± SD)
Commercial Alcoholic Beverage	1.94 ± 0.00^{i}
18A	1.79 ± 0.00^{i}
18B	1.73 ± 0.00^{i}
22A	2.43 ± 0.00^{i}
22B	2.19 ± 0.00^{i}
25A	2.54 ± 0.00^{i}
25B	2.50 ± 0.00^{i}

Values are means ± SD for n=3; values within same column with different superscript differ significantly ($p<0.05$)

Table 2 shows the alcohol content of the final fermented samples from the GC and triple scale hydrometer which ranged from 8.59% (18 ˚Brix B) to 12.52% (25 ˚Brix A) with the GC method and with the hydrometer, the values ranged from 9.92% (18 ˚Brix B) to 14.00% (25 ˚Brix A). Samples from the A must for the various ˚Brix concentrations had higher alcohol levels than those from the B must because prior to fermentation (day zero) before yeasts were added, the TSS for the A must increased slightly over the B must. The higher alcohol levels could be attributed to higher amounts of available sugars and the capacity of the yeasts to convert the sugars to alcohol. The alcohol content of the 25 ˚Brix A final fermented samples was significantly higher ($p<0.05$) for both methods compared to the commercial sample (see Table 6). Reported alcohol levels in various fermented beverages ranged from 7.17% for taro corms (Fiscal and Chavez, 2016), to 9.6% for hibiscus (Nobile et al., 2003) and 8.00% and 7.69% for yellow and rose red pawpaw (Kiin-Kabari et al., 2019), respectively.

3.4 Spectrophotometric and Colour Analyses of Fermented Beverages

The dasheen final fermented samples were colourless (nearly white to light yellow) and categorised as white fermented beverage when a 420 nm wavelength was used to determine the propensity to yellow or brown, with the higher absorbances indicative of 'yellowing' of the white final fermented samples (Blesic et al., 2013).

Absorbance readings of the final fermented samples at 420 nm are shown in Table 4. The 25 ˚Brix B sample made from must with cooked dasheen exhibited the highest absorbance and the most 'yellow' character. The lowest absorbance and least 'yellow' noted was the 25 ˚Brix A. From Table 6, the commercial product had a significantly ($p<0.001$) higher absorbance value indicating more 'yellowing' than the 25 ˚Brix A one. Blesic et al. (2013), evaluated the absorbances at 420 nm between non-filtered and filtered white wines and found the non-filtered wines showed higher absorbances than the filtered wines, however, the absorbance values obtained for the non-filtered wines were lower than the range in this present study.

For colour analysis, higher L* values (whiteness) although not significant were noted for the 22 and 25 ˚Brix A fermented beverages (see Table 4) versus the B ones which were cloudier due to the type of must used. The a* and b* components were very low, (a* values were closer to zero), which meant that the alcoholic beverages did not reflect strong red and yellow hues, hence were colourless. The one-way ANOVA revealed a *P*-value of 0.003 for the a* component, which indicated a significant difference when products from both A and B musts were compared with a lower a* component (degree of redness) for the A products. From Table 6, the L*, a*, b* components were significantly different ($p<0.05$) for the 25 ˚Brix A and the commercial product in that the L* component was clearer than the commercial one while the a* component showed

Table 4. Colour Analysis of the Commercial and Fermented Alcoholic Beverages Produced from the Dasheen Must

Parameters	**˚Brix**						***P*-value**
	18 A	**18 B**	**22 A**	**22 B**	**25 A**	**25 B**	
λ = 420 nm	0.375 ± 0.002^{a}	0.351 ± 0.003^{a}	0.250 ± 0.002^{a}	0.458 ± 0.004^{a}	0.246 ± 0.002^{a}	0.506 ± 0.008^{a}	.509
$\mathbf{1}_{L^*}$	87.02 ± 0.27^{b}	88.63 ± 0.35^{b}	88.99 ± 0.03^{b}	88.10 ± 0.04^{b}	88.59 ± 0.01^{b}	87.99 ± 0.04^{b}	.901
$\mathbf{2}_{a^*}$	0.23 ± 0.00^{c}	0.41 ± 0.01^{d}	0.07 ± 0.01^{c}	0.24 ± 0.01^{d}	0.03 ± 0.00^{c}	0.20 ± 0.00^{d}	.003
$\mathbf{1}_{b^*}$	5.89 ± 0.07^{f}	1.57 ± 0.53^{f}	2.25 ± 0.00^{f}	1.69 ± 0.02^{f}	1.36 ± 0.01^{f}	1.93 ± 0.00^{f}	.057

Values are means ± SD, n=3; values within same row with different superscript differ significantly ($p<0.05$)

Table 5. Sensory Evaluation Comparison of the 25 ˚Brix Fermented Alcoholic Beverages

Final Alcoholic Beverages	Appearance	Colour	Aroma	Taste	Mouthfeel
25 ˚Brix A	1.63 ± 0.81^{a}	1.57 ± 77^{a}	1.70 ± 0.09^{a}	1.67 ± 0.18^{a}	2.07 ± 1.05^{a}
25 ˚Brix B	3.13 ± 1.01^{b}	3.07 ± 0.94^{b}	2.43 ± 0.19^{a}	3.33 ± 0.37^{b}	3.47 ± 1.28^{b}
***P*-value**	.001	.001	.056	.001	.001

Values are means ± SD for n=30; values within same column with different superscript differ significantly ($p<0.05$)

Table 6. Comparison between the 25 ˚Brix (A) Fermented Dasheen Beverage and the Commercial Dasheen Beverage

Wine Property	25 ˚Brix (A) mean (SD)	Commercial mean (SD)	*P*-value
pH	$3.12\ (0.06)^{a}$	$3.77\ (0.06)^{c}$	.002
SG	$1.0053\ (0.0012)^{a}$	$1.0720\ (0.0012)^{c}$	≤ .001
TSS (˚Brix)	$10.13\ (0.06)^{d}$	$23.37\ (0.06)^{e}$	≤ .001
TA (% citric acid)	$0.75\ (0.00)^{f}$	$0.22\ (0.01)^{h}$	.001
Alcohol Content (%) - Hydrometer	$14.00\ (0.19)^{h}$	$11.50\ (0.15)^{i}$	.009
Absorbance at 420 nm	$0.246\ (0.002)^{j}$	$0.384\ (0.002)^{k}$	≤ .001
Alcohol Content (%) - GC Analysis	$12.50\ (0.01)^{l}$	$9.59\ (0.01)^{m}$	.001
L*	$88.59\ (0.01)^{n}$	$87.06\ (0.05)^{o}$	.005
a*	$0.13\ (0.00)^{p}$	$0.31\ (0.01)^{q}$	≤ .001
b*	$1.36\ (0.01)^{r}$	$3.06\ (0.10)^{s}$	.005

Values are means ± SD for n=3; values within same column with different superscript differ significantly ($p<0.05$)

a lower red hue and the b*component a lower yellow hue compared to the commercial product.

3.5 Sensory Analysis

Dasheen fermented alcoholic beverages made from the two musts (A and B) were significantly different ($p \leq 0.05$) on the sensory attributes for mouthfeel, taste, appearance, and colour. The 25 ˚Brix A product was preferred over the 25 ˚Brix B one, based on the lower sensory evaluation scores (highly liked) in Table 5. The 25 ˚Brix A product was also preferred because of its improved clarity (higher L*), the lower absorbance reading, indicating a lighter, less opaque wine (see Table 4), the higher alcohol levels obtained from GC and hydrometer methods (see Table 2) and the higher TSS readings compared to the B product (see Table 2). Even though final products from both musts were acidic, the 25 ˚Brix A was more acidic due to the lower pH value of 3.12 and similarly when compared to the commercial wine, the 25 ˚Brix A was more acidic (see Table 6). Overall, the data showed the 25 ˚Brix A final product as the ideal, acceptable product.

Dasheen is not high in compounds such as anthocyanins and polyphenols which add a heightened nutrient content compared to wines made from grapes, papaya and purple sweet potato and other highly pigmented fruits or storage roots as described in the literature (Ray et al., 2011). Recently, fermented tubers such as yam (Batista et al., 2019) and cassava (Yuwa-Amornpitak et al., 2012; Coelho et al., 2020) have been investigated. However, Batista et al. (2019) used lactobacillus instead of yeast. Since these crops are inherently low in flavour, infusions were done to ameliorate the sensory profile and increase the antioxidant content. In our study, amylase was also used to increase the available reducing sugars for fermentation.

While the flavour of the beverage made in this study may not be as dynamic and not as nutrient enriched, it may find utility as a cheaper alternative for a cooking wine. Additionally, the beverage developed can also be an alternative as a base ingredient, for the production of other alcoholic beverages in gastronomy such as cocktails and other preparations, such as alcoholic truffles, for example.

4. Conclusion

From the sensory evaluation, the 25 ˚Brix A final product was consumer acceptable with a pH, SG, TA and TSS reading of 3.12, 1.0053, 0.75% and 10.13 respectively. The alcohol content from the GC method was 12.52% versus 14% with the triple scale hydrometer. The absorbance reading at 420 nm was 0.246 with L*, a*, b* values of 88.59, 0.13 and 1.36 respectively.

The manufacture of an alcoholic fermented beverage eliminates wastage of this perishable crop, which is available yearlong, particularly when there is a glut in the market and offers opportunities for economic benefits to farmers and entrepreneurs. The product marketability can be improved with larger scale manufacturing since there is knowledge of the quality characteristics to make a standardised dasheen fermented alcoholic beverage. In advanced studies, the starchy dasheen corms can be gelatinised to produce a high glucose/sugar content before fermentation and without adjuncts can be used to produce distilled alcoholic beverages such as vodka. Further research is warranted using dasheen as the main fermentable sugar via enzymatic digestion in order to increase flavour and aroma from its own characteristic by the distillation process that is used for spirits.

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Rohanie Maharaj *is currently the Programme Coordinator of the postgraduate programme in Food Science and Technology at the Chemical Engineering department, and is actively involved in teaching, research, outreach and administration in the Food Science and Technology unit at the UWI, St. Augustine Campus. Professor Maharaj was awarded a grant by the Food and Agriculture Organisation (FAO) of the UN to conduct a series of capacity building webinars and discussion workshops on Food Packaging Practices in the CARICOM region in December 2020. She also*

received a grant from the Campus Research and Publication Fund Committee in 2022 on Rapid Testing of Contaminants. Apart from her twenty-five (25) years of academic experiences, Professor Maharaj brings fourteen (14) years of significant industry experiences, where she has worked in the manufacturing sector leading quality and reliability at a senior level. She is well trained in building quality at the international level and has also served in the capacities of Team Chair and Evaluator for external accreditations on behalf of the Accreditation Council of Trinidad and Tobago (ACTT).

Mark Dookeran *is currently a Public Health Inspector IV with the Ministry of Health in Trinidad and Tobago, where he is charged with identifying and assessing risks to human health in the environment and to use whatever methods which are reasonably practicable in order to control or eliminate these risks in a manner that would have minimal negative impacts on the environment. As a former lecturer in the Food Science and Technology programme at the UWI, St. Augustine Campus, Dr. Dookeran taught several courses such as Sanitation in Food Processing, Food Microbiology, and Food Quality Assurance. He also conducted research in these areas.* ■

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The Exigency for Resilient and Cyber-Secure Critical Infrastructure in the Caribbean

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Abstract: *Critical Infrastructures (CIs) are essential assets used to maintain vital societal functions, for example utilities such as power, water, gas, and telecommunication networks. CIs comprise two main parts, namely a: Cyber component and a Physical component, which allow them to operate. Therefore, the occurrence of faults or attacks in either domain can result in the disruption of services, causing negative impacts beyond the system itself. The purpose of this article is to raise awareness within Trinidad and Tobago and, by extension, the Caribbean on the importance of maintaining resilient and cyber secure CIs for the purpose of critical infrastructure protection (CIP) given the current situation. A review of past incidents from 2012 - 2022 taken place both regionally and internationally is discussed, with major emphasis on those occurring in the Caribbean region. These incidents have been presented from the perspective of faults and cyber-attacks affecting CIs resulting in the disruption of services. In responding to frequently occurring scenarios, recommendations on the way forward have been proposed.*

Keywords: *Critical Infrastructures (CIs), Critical Infrastructure Protection (CIP), Resilient Control, Cyber-attacks, Fault Tolerant Control*

Acronyms

CI – Critical Infrastructure
CIP – Critical Infrastructure Protection
CRU – Curacao Refinery Utilities
DoS – Denial of Service
FDI – False Data Injection
IPP – Independent Power Producer
PLC – Programmable Logic Controllers
LAC – Latin America and the Caribbean
PFTCs – Passive Fault Tolerant Control Systems
AFTCs – Active Fault Tolerant Control Systems
HFTCs – Hybrid Fault Tolerant Control Systems
SIDS – Small Island Developing State

1. Introduction

In the last 25 years, several reported faults (Tamronglak et al., 1996) and cyber-attacks have become a source of significant concern internationally and regionally. This has raised the awareness of potential threats and their effects on the critical infrastructures (CIs) within Small Island Developing States (SIDs) locally and regionally. These CIs are more important now than ever due to the COVID-19 pandemic and the increased reliance placed on them. A prime example of major CIs would be the primary health care systems, suddenly being exhausted of their resources. Inherently, CIs consist of both a physical and cyber domain that work together to perform a specific objective. The physical domain can be described as the physical processes implemented for such systems. For example, the energy grid, chemical process equipment, offshore oil and gas platforms. However, these physical processes can be subjected to faults that negatively affect equipment and the overall system objective. The cyber domain can be viewed as the components that do not directly interact with the physical world, such as data computations, monitoring communications, and communication protocols. Similarly, if subjected to cyber-attacks, it disrupts the cyber domain and, in turn, the overall system. Therefore, both domains play an integral part in the daily operations of CIs given the nature of their dependency on each other. This article is divided into three sections. Section 1 highlights the recent disturbances that have manifested themselves within local and regional CI from the perspective of faults and cyber-attacks. Section 2 highlights the concerns surrounding faults and cyber-attacks in the Latin America and Caribbean (LAC) region. Section 3 proposes a way forward based on

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recommendations, and lastly, the research is concluded. To the best of the authors' knowledge, no article has critically reviewed major CI incidents such as these that have taken place locally and in the wider Caribbean, with most cases focused on the English-speaking Caribbean islands and, by extension, countries within Latin America. The article aims to raise awareness for such situations and promote the need for resilient and cyber secure CI in the Caribbean in order to prevent the dangers that these issues present.

2. Recent Disturbances Locally and Regionally

CIs can be defined as complex, large-scale systems that require sophisticated supervisory control systems. These assets are essential for societal functions such as agriculture, water supply, public health, transportation, and electricity generation (Puig et al., 2016). Systems such as these can be subjected to disturbances that may affect their operation daily, resulting in critical situations. A disturbance can be described as a state in which the regular operation of any given system is affected. This article looks at two significant disturbances: 1) faults and 2) cyber-attacks. A fault can be described as the deviation of some specified parameter, whether performance indices or control objective from an acceptable value. Naturally, a fault can then lead to failure when not handled promptly.

In comparison, failure can be described as the system's inability to meet its intended objective under specific conditions. Therefore, failure by definition can be considered more detrimental as compared to a fault. Several faults have occurred locally and within neighboring Caribbean islands, which have resulted in unfavorable situations. These faults have been well studied in literature internationally (Haes Alhelou et al., 2019). Table 1 shows some of the significant power outages around the globe and their associated reported causes.

2.1 Faults Locally and Regionally

Studies have focused on power outages and their associated faults internationally. However, little attention has been placed on documented cases related to the Caribbean region. This section reviews past faults which have resulted in power outages within the LAC region. The following cases have been reported between the years 2013-2022. Over the years, Trinidad has experienced various power outages due to different situations, such as in 2013 (Kowlessar, 2013; Parasram, 2013). The root cause of the problem originated at Phoenix Park Gas Processors Limited which affected gas delivery to power generation units and their dependent sources. Similarly, in 2019, two significant nationwide power outages were recorded across Trinidad. On the 29th of May 2019, the first incident occurred where two power dips were experienced originating from the Desalination Company of Trinidad and Tobago (DESALCOTT) as a result of generator malfunction (Trinidad and Tobago Weather Center, 2019; Doughty, 2019). The second incident occurred in September, which affected Tobago. The issue originated from Cove Eco-Industrial Business Park, causing machines to go offline (Sambrano, 2019; Loop News, 2019). Recently in 2021, various locations across Trinidad were without power due to an issue that originated at one of the power plants (CNC3, 2021; Trinidad and Tobago Guardian, 2021b; TTT News, 2021). A similar situation was experienced in Tobago during maintenance work. A transformer tripped along with the lines from the Milford Bay Substation resulting in a power outage (Trinidad and Tobago Guardian, 2021a).

One of the most recent situations was a 12-hour nationwide power outage which occurred on the 16th of February 2022. The source of the issue was reported as a fault which caused T&TEC's 220 KV lines to trip, causing generation units to go offline (T&TEC, 2022). The water distribution as well as communication network within Trinidad was also impacted negatively. Jamaica has also experienced two severe power outages that took place in 2016. The first occurred on the 17th of April and the second incident took place on the 27th of August which was caused by a fault on the transmission system (Office of Utilities Regulation, 2017). In 2019, the Barbados Light and Power Company sustained power outages due to switch failure in one of the (Spring Garden) substations, while subsequent to that, due to a fault on one of its generating units (Phillips, 2019; BLPC, 2019). Similarly, Belize had several documented cases during 2016 - 2022. In each of these cases, different parts of Belize were reportedly affected by different faults. Areas such as San Pedro town (Belize Electricity Limited, 2016a) and Caye Caulker sustained power outages that lasted up to seven (7) hours (Belize Electricity Limited, 2016b) and in some situations over

Table 1. Significant Power Outages across the world

Country Region	Date	Duration (hours)	Affected People directly/ indirectly (million)	Reported Causes
Brazil	4th Feb 2011	16	53	Transmission line fault and fluctuated power flow
Holland	27thMarch 2015	1.5	1	Plant technical fault
Turkey	31stMarch 2015	4	70	Power System Failure
Ukraine	21st Nov 2015	6	1.2	Power System Failure
US (NY)	1st March 2017	11	21	Cascading failure in transmission system
Sudan	10th Jan 2018	24	41.5	Cascading Failures

Source: Abstracted from Haes Alhelou et al. (2019)

Table 2. A Compilation of Reported Incidents for the LAC Regio**n**

Ref.	Country	Year of Occurrence	Affected Organisation	Reported Causes	Effect of Situation
Trinidad and Tobago Guardian, 2020	Trinidad	July 2020	Methanol Holdings	Pipe Failure	Shut down of Operations
WASA, 2018	Trinidad	February 2018	Point Lisas Desalination Plant	Problem with internal control systems	Affected water supply to residents within Trinidad
Loop News, 2020	Barbados	2020	Barbados Light and Power Company Limited	Fault on the distribution system at the St. Philip substation	Power outage to several areas St Philip, St John St George
Belize Electricity Limited, 2019	Belize	2019	Caye Caulker	Failure of one of the generating units	Loss of Power resulting in load shedding
Belize Electricity Limited, 2022	Belize	2022	Caye Caulker	Failing electronic equipment	Seven (7) power outages
Curacao Chronicle, 2016	Curacao	2016	Curacao Refinery Utilities	Issue with gas turbine at the CRU plant facility	Two successive power outages affecting residents
Curacao Chronicle, 2018	Curacao	2018	Tera Kora substation and Zegu substation	Issue was not identified	Large part of the island was without power for approximately one hour

Table 3. Some Documented Cyber-attacks

Attack Situation	Descriptions of the Events
Siberian Pipeline Explosion (1982)	The first reported cyber security incidents involving a CI was the Siberian Pipeline Explosion which occurred in 1982. The intruder inserted a Trojan horse into the SCADA system.
October (2017)	The Australian Government revealed that hackers compromised an Australian national security contractor in 2016 and stole large amounts of sensitive data.
January (2020)	Mitsubishi announces that a suspected Chinese group had targeted the company as part of a massive cyberattack that compromised personal data of 8,000 individuals as well as information relating to sensitive projects.
May (2020)	Cyber criminals managed to steal $10 million from Norway's state investment fund in a business email.
February (2021)	Ten members of a cybercriminal gang were arrested after a campaign where stole more than $100 million worth of cryptocurrencies.

Sources: Adapted from Sánchez et al. (2019) and CSIS (2021)

the course of three (3) days (Belize Electricity Limited, 2021). Like Belize, Dominica has experienced two island wide power outages in 2015 due to a fault at its Sugar Loaf plant (Anon, 2015).

In 2019, a failure in the regional electrical interconnection system affected Honduras, Nicaragua, Guatemala and El Salvador (The Tico Times Costa Rica News, 2019). There have also been incidents reported in Curacao. The island suffered three successive blackouts (Neaves, 2020). In addition to these previously mentioned events Curacao sustained two power outages in 2019 (Nu.nl, 2020), two in 2020 and another in 2021 (Aquaelectra, 2021). St Lucia has also suffered major power outages. These blackouts experienced on the island occurred during 2019-2021. The island experienced three major island wide power outages as a result of various faults (Joseph, 2019 and 2021; Gaillard, 2020). These scenarios prove to be a concern for daily operations. Table 2 contains additional reviewed incidents, which have not been discussed previously.

2.2 Cyber-attacks Locally and Regionally

Cyber-attacks can be defined as an offensive maneuver that targets computer information systems, computer networks, infrastructures, personal devices, leading to potential loss and harm (Ekici and Altun, 2014). Internationally, Cyber-attacks have become more prevalent and have proven to be of significant concern. Over the years (1982-2021), several cyber-attacks have been documented (see Table 3). The previously mentioned incidents give a brief description of the cyber-attacks performed and the effects on various countries and organisations. It is evident that cyber-attack incidents are escalating and becoming very frequent. This section aims to review cyber-attack incidents for the LAC region for the period 2012-2022 and by extension, raise the level of cyber awareness. In 2012, several eastern Caribbean states were reported as attacked, such as Trinidad and Tobago, Dominican Republic, and Barbados. Trinidad and the Dominican Republic were subject to cyber-attacks which affected their government websites (Bureau of Democracy, 2012). Barbados experienced denial of service attacks affecting Lime Barbados's broadband network customers.

At the end of September 2012, over 1,000 cyber-attacks were reported to the cybercrime investigation and research unit, while 229 websites were reported as attacked, including government, private sector companies and tertiary institutions within Jamaica. Digicel was also subjected to cyber-attacks during 2012-2013. An attacker gained access to the company's database and stole sensitive information. In 2013, Barbados police were reportedly investigating missing data from the oil industry, while in the same period cyber-attacks had

targeted government agencies, financial institutions and private businesses. Within the same year, two Bulgarian nationals reportedly stole over US$ 150,000 from ATMs (Minto-Coy et al., 2018). Cyber-attacks initiated by hackers were also reported affecting various government websites within the Caribbean such as Jamaica (JIS, 2015), St Vincent (CARICOM, 2015) and the Bahamas (BIS, 2015). A similar situation developed in 2019 which affected 11 Trinidad and Tobago government websites, which were breached by Brazilian hackers resulting in these sites being temporarily, disabled (Neaves, 2019).

The government of Bahamas in January 2020, reported a cyber-attack which affected the registrar general's filing information executed by a malicious group (OAGMLA, 2020). The previously mentioned incidents show a trend of emerging and frequent attacks on various countries within the Caribbean. A report released by Microsoft presented data for the period January to March 2017 (OAS, 2018). The data revealed a malware encounter rate which was higher than the global average. Figure 1 shows the encounter rate experienced per country. A similar article (Toapanta et al, 2019) focused on cyber security for the LAC region. The article presented different cases of cybercrimes in Ecuador for 2017, based on location and the types of cyber-attacks, as seen in Figure 2. Essentially, 530 cases were reported where the Pichincha area sustained 145 cases, 24 cases in Manabi, 22 cases in El Oro, 18 cases in Guayas followed by the rest of the Provinces which reported smaller cases which were aggregated.

The popular crimes reported were that of personal, business and government theft. Additionally the cyber-attacks most used and registered in 2018 by banks within the LAC region can be seen in Figure 3. Figure 4 shows the number of web application attacks in the Caribbean in June 2019 based on targeted countries. Puerto Rico recorded the most significant number of attacks followed by Dominican Republic, Bahamas, Jamaica, Haiti, and

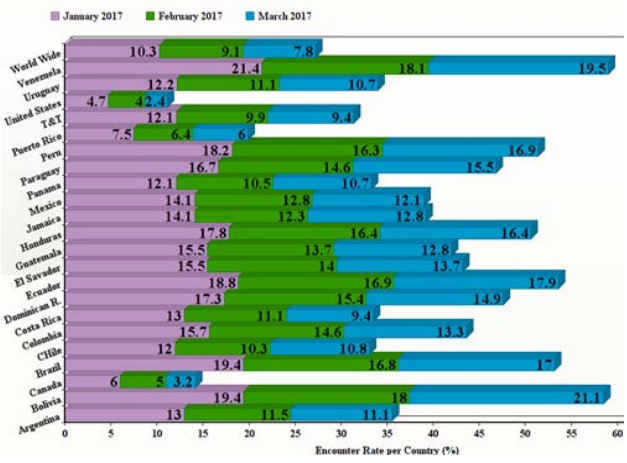

Figure 1. The Encounter Rate Experienced per Country from January to March 2017
Source: Abstracted from OAS (2018)

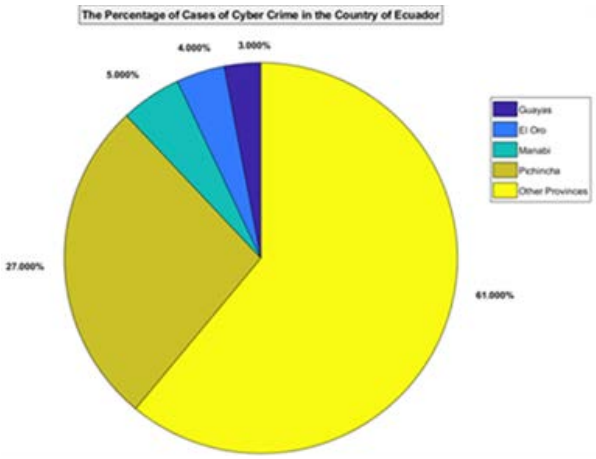

Figure 2. The Percentage of Cases of Cybercrime in the Country of Ecuador in 2017 (Source: Abstracted from Toapanta et al. (2019))

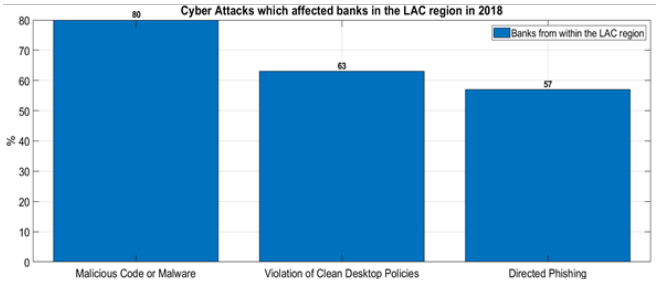

Figure 3. Cyber-attacks Affecting Banks in the LAC Region 2018
Source: Abstracted from Toapanta et al. (2019)

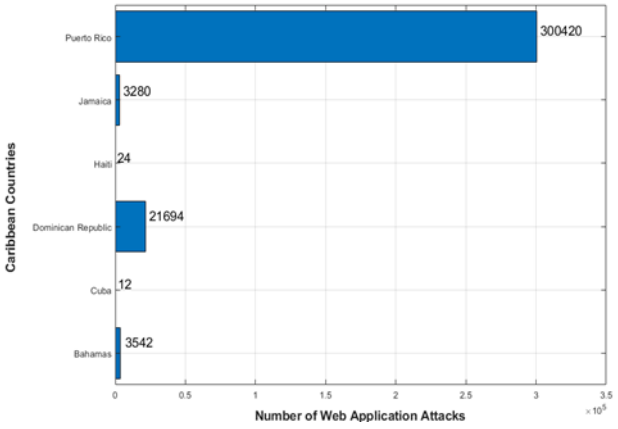

Figure 4. The Number of Web Application Attacks Recorded in June 2019 (Source: Abstracted from Statista (2021))

Cuba. The Caribbean has been highlighted as one of the locations being targeted by ransomware attacks (Hitachi Systems Security, 2020). One prime example of such an incident occurred in late October 2020 that affected one of Trinidad and Tobago's largest conglomerates. A cyber security incident which originated in Barbados migrated to Trinidad, resulting in 17,000 critical files being leaked causing disruptions in its subsidiaries' operations. There was a noticeable increase in advertisements for stolen data

from LAC organisations involving ransomware which increased to 550% from the first quarter of 2020 to the first quarter of 2021 (Caparros, 2021). Figure 5 depicts the websites associated with more than 15 different varieties of ransomware advertising data allegedly stolen from regional organisations.

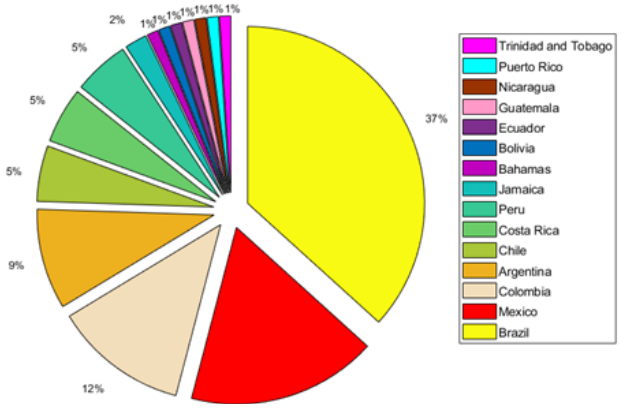

Figure 5. The Percentage of Ransomware Data Theft ADS in LAC by country. Source: Abstracted from Caparros (2021)

The Trinidad and Tobago Cyber Security Incident Response Team published an advisory notice, highlighting that an increase in ransomware attacks targeting Caribbean organisations had been detected (TTCSIRT, 2020). In addition to ransomware, various schemes within the LAC region were reportedly being used to trick individuals and businesses into transferring money known as social engineering attacks (Caparros, 2021). Massy Stores suffered a cyber-attack causing a halt in their business operations of over 21 branches which occurred on the 28th of April 2022 (MST, 2022).

3. Concerns Surrounding Faults and Cyber-attacks in the LAC Region

3.1 Concerns Surrounding Faults

In the previously mentioned incidents reviewed in Section 2, there have been quite a number of power outages which have been caused due to various types of occurring faults. One of the major concerns for such situations, which have become apparent is the aspect of interdependencies. Essentially, this can be thought of as a connection between two or more infrastructures, where the state of one influences the other (Rinaldi et al, 2001). Therefore, in such a situation as it relates to CIs there may exist bi-directional relationships between other CIs and so naturally when one system is affected the dependent sources will experience the effects indirectly due to the nature of the event taking place. Hence, the effects can be felt over large geographic regions and by extension have an impact nationally and globally. It is important to fully understand that there exist various types of interdependencies, such as Physical, Cyber and Geographical and their major differences. Physical interdependency can be considered as where the state of each is dependent on the material output of the other, while cyber interdependency can be defined as where the state and operation of the system is dependent on the information transmitted.

Geographic interdependency can be defined as whereby the local environment can affect changes in all systems within the area (Ouyang, 2014). Identification of such dependencies can be considered a key step into understanding the complex interconnections which may exist between CIs. As a result of such interdependencies, another major issue which has been brought to the forefront is that of power failure. Power failure, based on reported cases highlighted in Section 2, has been widely caused by faults leading to failures within the CI.

Failure of Power systems can be seen as critical as human activities are dependent on power supply, which can be devastating (Haes Alhelou et al., 2019). Such blackouts can lead to social, economic and political impacts which may affect all systems. Therefore, it is evident that the interdependencies, which exist when coupled with the nature of the fault, may produce cascading blackouts. In such a situation the power outage starts as a single system failure and propagates throughout the entire system. It is imperative that faults be handled in a timely manner as if not done the effects can be detrimental.

3.2 Concerns Surrounding Cyber-attacks

The previously mentioned situations highlight the frequency, magnitude and types of cyber-attacks within our region, which is clearly becoming a major concern from the perspective of cost and damage. In 2016, it was reported that the LAC region became a new frontier for cyber-attacks at an estimated cost of $US90 billion per year while, 12% of distributed denial of service attacks (DDoS) were reported as having targeted this region and was on the rise (Jessop, 2016). PricewaterhouseCoopers (PWC) reported that Caribbean firms were not paying enough attention to cybersecurity risks (Curaçao Chronicle, 2017), given the increasing ransomware attacks affecting organisations. In addition to ransomware attacks our region has been plagued with a wide variety of attacks such as Web application, phishing, DoS and even malware attacks. Web application attacks have been mentioned quite frequently in most of the reported cases making it one of the most popular cyber-attacks within our region.

In 2021, the 24th Annual Global CEO Survey for the Caribbean explored the views of 5050 chief executives with Cyber threats listed as one of the top concerns due to high profile cyber-attacks. Figure 6 highlights the areas of concern (PwC, 2021). The Global Cybersecurity Index (GCI) can be used as indicator that measures the commitment of countries to cyber security in order to raise cybersecurity awareness (GCI, 2019). Table 4 compares

the GCIs for 2018 and 2020 for nations within the American Region. The first comparison shows that in 2020 Jamaica's index was calculated as 32.53, which reduced by 8.17 from its 2018 index of 40.7. The table also shows that for every country highlighted, their global associated rank dropped over a two-year period with the exclusion of St Kitts and Guyana.

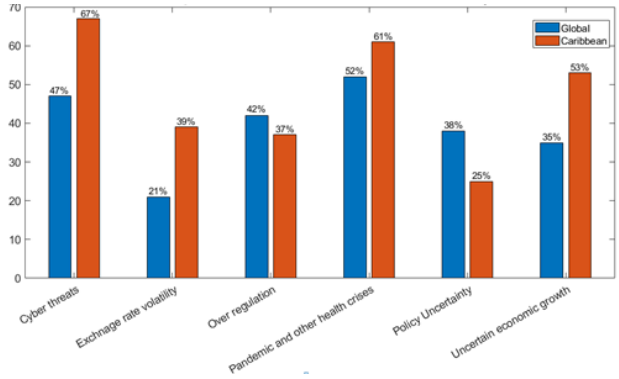

Figure 6. The Top Concerns from the 24th Annual Global CEO Survey conducted in 2021. Source: Based on PwC (2021)

Table 4. Global Cybersecurity Index Comparison for 2018

Country Name	Overall Score	Regional Rank	Global Rank
Jamaica	32.53 (▼8.17)	15 (▼4)	106 (▼12)
Antigua and Barbuda	15.62 (▼9.08)	23 (▼6)	142 (▼29)
Trinidad and Tobago	22.18 (▲3.38)	20 (▼1)	125 (▼2)
Barbados	16.89(▼0.41)	21 (▼1)	139 (▼12)
St. Vincent & the Gren.	12.18 (▼4.72)	28 (▼7)	154 (▼25)
Bahamas	13.37(▼1.33)	24 (▼2)	147 (▼14)
Grenada	9.41 (▼4.89)	31 (▼8)	163 (▼29)
Guyana	28.11 (▲14.9)	17 (▲8)	114 (▲24)
Saint Lucia	10.96 (▲1.36)	29 (0)	158 (▼9)
St Kitts and Nevis	12.44 (▲5.94)	27 (▲3)	153 (▲4)
Dominica	4.2 (▲2.3)	34 (▼1)	174 (▼2)

Sources: Abstracted from GCI (2019 and 2021)

In 2019, a conference on cybercrime strategies for the Caribbean was conducted with the aim of creating a regional response to combating cybercrime by identifying the elements required for an appropriate strategy (CARICOM, 2019). The conference highlighted that most Caribbean countries were at an elementary stage when dealing with cyber-crime. In other cases, there was no cyber-crime legislation established by some participants, while some of the neighboring countries did not provide any data. Table 5 lists the Caribbean nations that contain a national cyber security strategy and the ones currently in the development stages, thus, exposing the region's growing inability to address cyber-attacks. These previously mentioned scenarios highlight the gap that exists as it relates to CIP and the issues which countries within the Caribbean face.

4. Recommendations for the Way Forward

Based on the previously highlighted scenarios and concerns surrounding cyber-attacks and faults, it is imperative CIs be protected from such disturbances. It is clear that the LAC region faces significant adversary activities and so organisations operating in our region should be very weary of this dynamic environment. These incidents, as mentioned earlier (faults/cyber-attacks), especially in the case of cyberattacks, are getting increasingly complex and possibly detrimental due to the level of interconnectedness of the cyber and physical domains. Keeping these concerns in mind, this section proposes recommendations to help alleviate situations in the presence of such disturbances.

It is critical to understand that hackers who in most cases are the initiators of cyber-attacks do not follow any rules or guiding principles, making it a difficult situation to handle. Therefore, the need for having resilient cyber secure CIs is essential for not just CIs but organisations large and small, be it from public or private sector. The owners and operators of CIs and by extension, businesses must understand the potential risks, and ensure that improvements are made to the physical and cyber domains from the aspect of fault tolerance and cyber resilience. In order to attain some level of cyber resilience, the development of a proper defense mechanism is required and so three components must be considered: 1) Prevention, 2) Resilience and 3) Attack Detection and Isolation mechanisms. Prevention mechanisms have been used to alleviate against attacks, starting at an infiltration stage stealing vital information from the system which may be used to perform future attacks. Prevention deals with postponement of the attack (Dibaji et al., 2019). Essentially, prevention mechanisms can be grouped into two categories: 1) Cryptography and 2) Randomisation.

Table 5. Caribbean and Latin America Countries Containing a Cyber-security Strategy and Those in the Developmental Stage

Countries	**Country with a National Cybersecurity Strategy**	**Countries**	**Developing a National Cybersecurity Strategy**
Trinidad and Tobago	Yes (2013)	Guyana	Yes
Dominica Republic	Yes (2018)	Suriname	Yes
Jamaica	Yes (2015)	Ecuador	Yes
Panama	Yes (2013)	Peru	Yes
Costa Rica	Yes (2017)	Belize	Yes
Colombia	Yes (2016)	Barbados	Yes
Guatemala	Yes (2018)		

Source: Abstracted from IDB (2020)

Cryptography is the science of constructing and analysing protocols that prevent third parties from reading private messages (Nadia and Sadkhan, 2020). Cryptographic algorithms make use of the encryption/decryption process of messages.

Encryption is the process of encoding information from sender to receiver ensuring no third party can retrieve the transmitted information. Decryption is the reverse process of encryption which decrypts the information using a secret key that can only be manipulated by the sender/receiver (Laad et al. 2021). The cryptographic system contains the following basic basic components: 1) Plain text, 2) Cipher text, 3) Encryption, 4) Decryption, and lastly 5) Key.

Figure 7 gives a description of the encryption process. There are two types of encryption techniques, symmetric cryptography which is also known as shared secret encryption due to its encryption and decryption keys being the same. The second is known as asymmetric cryptography. In this type of encryption the key is divided into two different keys known as a public and private key. The information is encrypted by the user's public key while it uses its private key to decrypt the information (Arora, 2022). Recent literature (e.g., Hamouda (2020) and Patil et al. (2019)) put forward potential solutions for cryptography. Tables 6 and 7 show the comparison between symmetric and asymmetric algorithms.

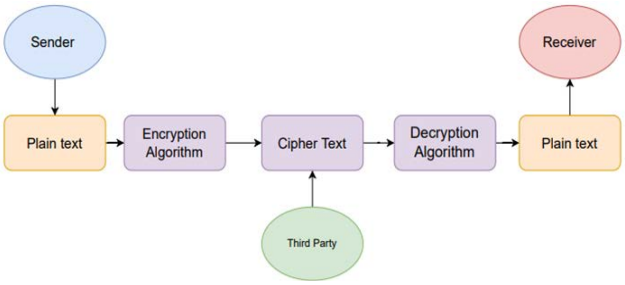

Figure 7. The Encryption/Decryption Process

Randomisation is used as a defensive tool to confuse the potential attacker and has proven useful whenever the predictability of the system may be manipulated by the attackers to obtain key information (Wang et al., 2020). Randomised algorithms have been very useful in a range of mathematical and algorithmic problems also being considered a robust control technique (Dibaji et al, 2019) which has been deployed over the years. Randomisation of data has proven to be successful as it relates to providing confidentiality. There are quite a number of methods which has used randomisation as a means of handling cyber-attacks over the years. These attacks include memory error attacks (Cadar et al, 2008), buffer flow attacks (Fen et al, 2012), attacks from botnets (Al-Jarrah et al, 2015), attacks targeting known static attributes of network devices and systems (Chavez et al, 2015), SQL injection attacks (Perkins et al, 2016), single step and iterative attacks (Xie et al, 2017), code reuse attacks (Yun et al, 2020) and adversarial examples which can affect deep neural networks (Lee et al, 2022).

Resilience can be thought of as a characteristic defined by its ability to withstand and recover from undesirable events (Wei and Ji, 2010). This characteristic may not be inherent and may require integration into the control system design and by extension brings about the topic of Resilient Control Design. Resilient Control is currently being investigated as means by which cyber-attacks can be dealt with (Yuan, Sun and Liu, 2015; Zhao et al., 2022). A resilient control system is one that maintains state awareness and an accepted level of operation normalcy in response to disturbances, including threats of an unexpected behaviour (Rieger, Gertman and McQueen, 2009).

There have been several popular resilience mechanisms which can be used as: 1) Game theoretic approaches, 2) Event triggered control and 3) Trust based approaches are just to name a few. Game theory methods

Table 6. Comparison of Different Symmetric Algorithms

Methods	DES	3DES	AES	IDEA	Blow Fish
Structure of Algorithm	Balanced Feistel	Feistel	Substitution, Permuation	Lai Massey scheme	Feistel
Advantages	Short key	Improved encryption of DES	Larger encryption, faster than 3DES	More secure than AES	Not prone to attacks
Disadvantages	Simple encryption, short key, slow	Slower than DES, susceptible to theoretical attacks	Susceptible to side channel attacks	Frail keys	Considered quicker aside from changing keys

Source: Adopted from Chandra et al. (2014)

Table 7. Comparison of Different Asymmetric Algorithms

Methods	Diffie-Hellman	RSA	DSA	ECC
Structure of Algorithm	Discrete logarithmic	Integer factorisation	Digital Signature	Elliptical curve
Advantages	Short key, fast algorithm	Difficult to decipher private key	Very fast and provides non repudiation and authenticity	Larger key with faster speed, and consumes less power
Disadvantages	Requires short time to decipher key. Susceptible to Man-in-the-Middle Attack	Complexity of key generation	Short lifespan of keys	Higher complexity and increases size of message

Source: Abstracted from Chandra et al. (2014)

focus on strategic interaction between multiple decision makers known as players. The player aims to optimise their objective functions which are dependent on their choices within the game. Game theory allows for a powerful modeling tool which helps describe interactions between players (Mohammed et al., 2022). Game theoretic approaches depend on the structure of the system or based on the type of malicious action which is acting on the cyber layer. The first approach is to model the game tailored for the system under consideration (Sanjab et al, 2017). The second is to model based on the type(s) of the attacks (Dibaji et al., 2019; Miao et al., 2018).

Even triggered control (ETC) has been receiving increased attention for real-time control systems. This type of control allows the control law to be only executed as needed as compared to time-triggered control. Hence, ETC is known for reducing the number of control tasks while maintaining the system's stability. It can be considered reactive and can generate a sensor sampling and control actuation when plant states deviate from a predefined threshold (Heemels et al., 2012). ETC is being used as a method for handling cyberattacks. Based on the frequency of attacks, event-triggered schemes are more appropriate than time-triggered methods for increasing resilience. There are a number of existing event triggered communication mechanisms which can be used to handle cyberattacks such as Denial of Service (DoS), False Data Injection (FDI), and Hybrid attacks. These methods may include communication strategies such as hybrid-triggered (HTS), adaptive event-triggered (AETS), dynamic event-triggered (DETS), memory-based event-triggered (METS), switching-like event triggered (SLETS), and stochastic event-triggered (Wu et al., 2022). Table 8 shows the associated cyberattacks and the event-triggered schemes used for each strategy.

Trust can be viewed as a relationship between two entities where one is considered the evaluator (trustor) and the other is evaluated (trustee). Trust is a relationship established between participating entities facilitated by network activities. The relationship is based on the former interactions and the behaviour exhibited by the participants within the network.

A node may acquire a cumulative value which represents the node's reputation in the given network. Trust modeling helps with the development of functional

Table 8. Cyber Attacks and Associated Communication Strategies

Cyber Attacks	Event Triggered Method	References
DoS	SLETS SETS	(Peng and Sun, 2020) (Peng et al, 2021)
FDI	AETS METS	(Qi et al, 2021) (Wang et al, 2020)
Hyrbid	HTS DETS	Wu et al,2020 Zhang et al 2021

Source: Abstracted from Wu et al. (2022)

parameters that will facilitate aspects such as trustworthiness, user-friendliness and reliability (Muzammal et al., 2020). The aspect of trust should be maintained at three levels: 1) data perception, 2) communication and 3) data fusion (Souissi et al., 2019). There are different trust models which can be used such as the Markov chain model, Arithmetic/Weighting, Directed and Undirected graph-based, Swarm intelligence, Neural Network, Probability based, Fuzzy based, Entropy, Game theory and lastly Bayesian trust model (Shayesteh et al., 2020).

Trust-based approaches have been investigated for scenarios not only limited to cyber-security but also in compromised sub-systems. This approach is comparable to redundancy-based approaches such that, if the numbers of attacks are not significant, then accurate data can be transmitted by trusted nodes within the system (Dibaji et al., 2019). Table 9 highlights some of the methods used for trust based approaches.

Lastly, attack detection and isolation is very important for a proper defense mechanism. It is imperative that these cyber-attacks be detected and located in a timely manner such that the damage sustained to the system can be controlled. Therefore, ensuring CIs have the ability to detect the deviation of its systems states plays a crucial role in maintaining the performance of the CI (Ding et al., 2018). Some of the popular attack detection and isolation strategies may include: 1) Weighted least squares approach (Pei et al., 2021), 2) Quasi Fault Detection and Isolation (Taheri et. al, 2020) and 3) Bayesain detection with binary hypothesis (Han et al., 2021).

For measurement data, a weighted least squares (WLS) approach is one efficient scheme for the defense of attacks. The weighted least squares approach uses a

Table 9. Methods Using Trust-based Approaches for Defending against Cyber Attacks

Techniques	**Attacks Considered**	**Pros and Cons**
Trust based RPL protocol (Airehrour et al, 2018).	Black Hole attack, Selective forward attack.	Evaluation for colluding attacks, energy consumption and E2E delays. Significant packet loss rate, limited mobility of nodes.
Trust for entities is computed using Bayesian Learning and Damper Shaffer Theory for data fusion and computing data trust (Shayesteh et al., 2019).	Malicious Behaviour	Data centric trust management. No consideration for dynamic mobile, and heterogeneous IoT environments
Introduces trust evaluation for secure routing topology construction (Djedjig et al., 2020).	Black hole attack, rank attack.	Efficient in terms of Packet Delivery Ratio, energy consumption, rank changes and throughput. Lack of consideration for mobility factor.

Source: Abstracted from Muzammal et al. (2020)

measurement residual that is usually constructed with the help of WLS observers and then compared to a predetermined threshold to determine the existence of an inaccurate measurement (Ding et al., 2018). This method is considered one of the most popular static state estimation methods which have been used for attack detection. Similar methods that fall under this category include the MF (median filter) and the ML (maximal likelihood) estimation (Du et al., 2022).

There have also been dynamic state estimation methods which have been used to detect the deviation of its systems as seen in the Table 10. Bayesian detection is a traditional detection method as it has been widely applied in data fusion, in sensor networks subjected to cyberattacks (Ding et al., 2018). Statistical anomaly detection models have been becoming increasingly popular in the field of cyber security research.

Some of the popular Bayesian models include: 1) Latent Dirichlet allocation (LDA), 2) Bayesian clustering, and 3) Poisson Factorisation. Bayesian models have the ability to represent uncertainty in a probabilistic manner. Making Bayesian methods attractive for incorporating them in anomaly detection frameworks as the uncertainty can be propagated to predictions resulting in them being more stable. Bayesian models also allow the combination of different types of information in a single framework which allows for a general form for reasoning known as Bayesian reasoning (Perusquía et al., 2022).

Similar to that of cyber resilience, fault occurrence has resulted in mainly power outages from the reviewed cases. The use of Fault Tolerant Control should be incorporated into the design of CIs to help promote the robustness of systems to such disturbances.

There are currently different types of FTC methods. The three main FTC methods are: 1) Passive Fault Tolerant Control (PFTC) methods, 2) Active Fault Tolerant Control (AFTC) methods and 3) Hybrid Fault Tolerant (HFTC) Control methods (Mohammed et al., 2022). In a situation where the nature of any faults occurring is fully known, PFTCs can be utilised, executing the prior defined handling methods which prove to be a major advantage given the control methods use the same conditions in both fault and normal operations. However, this method is susceptible to faults which are not considered and accounted for in the design process and serves as a major disadvantage (Amin and Hasan, 2019). One popular PFTC method is sliding mode control (Merheb, Noura and Bateman, 2013). It provides superior performance compared to other control structures but suffers from an issue known as chattering problem. Other methods which use PFTC include: 1) Linear quadratic control, 2) Fuzzy logic control, 3) Lyapunov based control and even control allocation that have been used in this type of design (Abbaspour et al., 2020).

In a situation where the faults being experienced are unknown and cannot be accurately handled, AFTCs can be used. It uses a fault detection and isolation module along with a reconfiguration law to eliminate the effects of faults. Some popular approaches for AFTCs include: 1) Kalman Filter method (Yuan et al., 2017), 2) Observer based design methods (Wang et al., 2015), 3) Fuzzy Logic method (Liu et al., 2019) and 4) Artificial Neural Networks method (Yin et al., 2016). Table 11 gives a summary of these methods.

Furthermore, HFTCs can be used in situations to combine the effects of PFTCs and that of AFTCs to handle

Table 10. A Comparison between Static and Dynamic Estimation Methods

Category	Methods	Advantages	Disadvantages
Static	WLS MF / ML	Low time complexity Good implementation	Low estimation accuracy Low suitability for large system design
Dynamic	Kalman Filter Extended KF Unscented KF	Good estimation accuracy Applicable to nonlinear models Good Detection rate	High time complexity Easy Divergence

Source: Abstracted from Du et al. (2022)

Table 11. A Comparison of AFTC Methods

FDI Methods	Linear Process	Nonlinear process	Mathematical Modelling	Advantages/ Disadvantages
Kalman Filter	Can be used for linear processes (Typical Kalman Filter)	Can be used for nonlinear processes (Unscented and Extended Kalman Filter)	Model based method which is required for FDI	Considered robust, however considered to be less accurate when compared to other FDI methods. This would result false alarms.
Observer	Can be used for Linear Process	Can be used for nonlinear process Nonlinear unknown input observer)	Model based FDI method for detection and diagnosis	Simple design and considered accurate, however modelling errors and uncertainties can result in slow detection and false alarms.
ANNs	Can be used for linear processes	Can be used for nonlinear processes	Data driven method used for FDI	Considered highly accurate, requires no model for implementation. Requires a large amount of historical data from the system performance.
Fuzzy Logic	Can be used for linear process	Can be used for nonlinear process	Data based method for FDI	Requires no model and so aspects such as disturbances, noise, uncertainties has no effect on the method. However, requires some expert knowledge of the system for implementation of rule base.

Sources: Abstracted from Mohammed et al. (2022) and Thirumarimurugan et al. (2016)

both situations simultaneously (Amin and Hasan, 2019). HFTC operates on the basis of using a passive controller which can be exploited for safe and reliable control until a reliable controller is acquired based on the information generated by the FDI unit. Naturally, the controller has more time to attain information from the fault and so a reconfigured law can take effect (Tahri et al., 2018; Alsuwian et al., 2022).

Adopting the previously mentioned FTC methods and the cyber resilience methods, allow CIs to handle a wide range of disturbances from the cyber and physical domain and by extension promotes CIP. In addition to these methods, there have been a number of best practices which can be used as a guide for CIP as suggested in (OAS, 2018). These practices include:

1) Identifying the clear division of responsibilities which involves government leadership in accordance with multiple stakeholders working together to develop a CIP strategy.
2) Creating a holistic approach using viewpoints from all sectors as the operation of CIs involves several entities such as public private sectors and academia.
3) Development of frameworks guidelines and procedures coordinated by the government with emphasis being placed on risk management.
4) Set a Security baseline which helps in managing cybersecurity risks.
5) Supporting dynamic solutions which are able to rival the ever changing cyber environment.
6) Fostering Trust between public private partnerships which facilitates the exchange of information in an open manner.
7) Development of early warning mechanisms which minimises the impact of cyber-attacks.
8) Investing into in human and technical resources such as cybersecurity as CIP requires experts from several fields of study. Therefore, this may require tertiary level institutions to offer extensive programmes within this field.
9) Improve cyber resilience, and
10) Participate in an international network.

These practices have been advocated in literature (Brunner and Suter, 2008; OAS, 2009; CIIP, 2015; Luiijf et al., 2016; Garcia and Jeun, 2016; Barrett, 2018; Cheng et al., 2021) and can be used to give insight to CIP strategies.

By application of these practices, CI organisations could foster a suitable defensive system. The disseminated knowledge of responsibilities and the concurring consequences would give a clear indication of the importance of fulfilling one's roles and thus serve as a means in which incorrigible practices could be prevented. The government's role by extension plays a bigger part in CIP being one of the bodies which are required to coordinate partnerships among sectors, both private and international, as well as update and disseminate information. Finally, the development of a continuously improved cybersecurity framework which serves as the main shield against cyber attacks at all stages from early detection and warning to prevention and isolation/handling is essential.

Fostering competent personnel, forming industrial partnerships and developing cutting-edge technology are each equally costly. That with the addition of trust may prove to be even more difficult as there is a reluctance of companies to divulge trade secrets as well as exposing potential vulnerabilities that may exist within their infrastructure, as situations like these can be used in the context of experience gained to help better prepare for similar future events. There is a need to prioritise the aforementioned practices. One of the most important aspects is investing into human and technical resources to foster an intrinsic CIP workforce. Table 12 provides some training solutions for Cyber Security and CIP.

It is also one of the options in which the benefit is directly obtained by the investing CI organisations. By achieving practice (8), this paves the way for developing a self-sustaining cybersecurity system since practices (4), (7) and (9) would be achievable based on the level of investment placed on training. The issue of trust varies based on the organisations involved, and further highlights the importance of the governing body that will be required to coordinate and manage partnerships to help foster the aspect of trust amongst participating entities. These partnerships will prove to be extremely useful from all aspects. The remaining practices involve government participation which will ensure CIP.

5. Conclusion

In this article, a detailed review of previous incidents that have taken place in the form of faults and cyber-attacks over the years has been conducted. The Caribbean region

Table 12. Description of training solutions for Cyber Security and CIP

Work	Proposed Solutions	Descriptions
(Willems et al, 2011)	Tele lab: system for hands on IT security training in a remote virtual lab environment	Structured virtual training followed by detailed practical exercises
(Tang et al, 2017)	Interactive cyber security defense training inspired by web based learning theory	Training attack and defense via a multitude of databases for facilitating vulnerability and exploitation.
(Proctor, 2016)	CS awareness Training Programme Efficacy Evaluation	Awareness of need, stratification and possible future of CS measures.
(Beuran et al, 2018)	CyTrONE: integrated cybersecurity training framework	Individual tailored training of attack, defense and forensic analysis of CS development in dynamic training environments.

Sources: Abstracted from Chowdhury and Gkioulos (2021

is under attack and faces a difficult task related to CIP. Necessary measures such as policies and strategies must be put in place to help combat these incidents and mitigate the effects of such occurrences. Entities such as CI owners/operators and, by extension, businesses must see the need to maintain resilient cyber secure organisations given the ever-changing environment to ensure that daily operations are not affected. Resilient control and Fault tolerant control can be used as two critical methods to reduce the effects of such scenarios in accordance with the general guidelines proposed for CIP. Future work includes a second article which reviews and analyses the theory of fault tolerant and resilient cyber secure methods that will help protect CIs from adverse situations.

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Fluid Flow and Heat Transfer Characteristics of Clerestory-Shaped Attics Heated from Below

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Abstract: *In this study, a finite volume analysis of the aerodynamics and heat transfer in attics of a clerestory roof design with pitch angles 14^o, 18^o, 30^o and 45^o and Rayleigh number range 3 x 10^5≤ Ra ≤2 x 10^7 is carried out. The shape of the enclosure has strong influence on the structure of the flow and temperature fields. The flow field is characterised by counter-rotating vortices enclosed by aerodynamic boundary layers. The size, strength and direction of rotation of the cells are controlled by the forces propelling the thermal plumes and the cold jets. The reduction of the number and size of the counter-rotating cells and their formation within the enclosures provide an analogous reduction of the total heat transfer rate as the roof pitch angle increases. The velocity and temperature profiles across midheight and midlength of the enclosures enable the prediction of appropriate position in the attic with the right condition to place sensitive items. On the heat transfer, the relationship between the mean Nusselt number and the Rayleigh number is presented in form of a correlation. Results obtained in the study are of significance to building engineers engaged in the analysis and design of building attics and tropical agriculturalists for the control of produce drying rates.*

Keywords: *Heat transfer, heated below, natural convection, pitch roof, clerestory-shaped*

Nomenclature

AR	Aspect ratio, AR =2H/L
g	Acceleration due to gravity, m/s²
H	Height of enclosure, m
k	Thermal conductivity, W/mK
L	Length of enclosure, m
Pr	Prandtl number
Ra	Rayleigh number
T	Temperature, K
T_C	Temperature at the cold wall, K
T_H	Temperature at the hotwall, K
u	Velocity in x-axis, m/s
U, V	Dimensionless velocity
V	Velocity in y-axis, m/s
X, Y	Dimensionless Cartesian coordinates

Greek symbols

α	Thermal diffusivity, m²/s
β	coefficient of thermal expansion, K
θ	Dimensionless temperature
ν	Kinematic viscosity, m²/s
ρ	Density, kg/m³
ϕ	Pitch angle, degrees

1. Introduction

The study of transport process in the attics has gained enormous attention over the years due to its vast areas of its applications. For example, in the rural communities of Sub-Saharan Africa, agricultural produce is often carefully arranged within the attic either for drying or for long-term storage for future use. In many Europeans cities, the attic space is sometimes used as a penthouse or for storage of items not being frequently used. The thermal characteristics of the attics vary with the climatic region and the nature of the heat flow in and out of an attic space generally affects the environmental condition of the space directly below it. As a result, the knowledge of the heat convection within the attic is necessary in order to correctly predict its effect on the thermal comfort and energy efficiency of the system.

The geometry of an attic depends on the shapes and orientation of the pitch roofs which differ from one part of the world to the other. Foundational experimental and numerical works on regular triangular-shaped pitch roofs include those of Flack (1980), Akinsete and Coleman (1982) and Poulikakos and Bejan (1983). Using the Galerkin weighted residual finite element method, Del Campo *et al.* (1988) obtained steady-state solutions for all possible seven thermal boundary conditions for a triangular enclosure. They observed that the intensity and rate of heat transfer in the enclosures heated from the base wall are much higher than in the enclosures heated from the side walls. The extensive reviews carried out by Kamiyo *et al*. (2010) and Saha and Khan (2011) indicate

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that most studies carried out up till that time on heat transfer in roofs were of isosceles triangular shapes despite the existence of many buildings with complex-shaped roofs.

Thereafter, a number of authors have studied unconventional attics. Yesiloz and Aydin (2013) performed experimental and numerical analyses of natural convection in a right-angled triangular-shaped enclosure isothermally heated at the base, cooled on the vertical wall while the inclined wall is adiabatic. The flow structure shows that the vortex at the middle of the enclosure widens while the shape also deteriorates. As the Rayleigh number (*Ra*) increases, thermal stratification becomes more intensive near the heat transfer surfaces. Using the Bejan's heatline approach, Basak *et al.* (2013) investigated natural convection in similar right-angled triangular enclosures but with a concave and convex inclined wall. The results show that for all parameters considered, thermal mixing in the enclosure with the convex hypotenuse is higher than in the concave case. Mirabedin (2016) developed a correlation for Nusselt number in terms of aspect ratio and Rayleigh number for heat transfer in the same right-angled triangular enclosure. Sieres *et al.* (2016) applied analytical and numerical methods to study laminar natural convection of air in vertical upright–angled triangular enclosures to show that, at low *Ra* and for lower angles, the heat transfer rate increases but at high *Ra*, it remains constant. Das *et al.* (2017) reviewed natural enclosure in some other irregular shapes.

Other complex roofs that have been investigated include inclined triangular (Mahmoudi *et al.*, 2013), dome (Das and Morsi, 2002), gable (Amrani *et al.*, 2017), trapezoidal (Mehryan *et al.*, 2020), section-triangular prismatic (Cui *et al.*, 2019), vaulted (Elnokaly *et al.*, 2019), paraboloid roof (Colliers *et al.*, 2020) and flat-top (Kamiyo, 2021). In spite, there are other common complex roofs that have not been adequately studied. The clerestory-shaped roof is one of such. This study, therefore, aims to investigate the aerodynamics and heat transfer within the attic of a clerestory-shaped roof under winter condition.

2. Methods

A long horizontal air-filled attic with a clerestory-shaped triangular cross-section shown in Figure 1 is investigated in this work. The cross-section is simply an isosceles triangle truncated by a vertical line. In real life, the location and height of the vertical wall vary. In this study, the vertical wall is at two-third of the base length and its height, h, is half of the enclosure height, H. Based on Penot and N'Dame (1992), since the width of the roof is less than half of its length, the flow and thermal fields could be taken as two-dimensional.

The air within the enclosure is regarded as a viscous, incompressible and Newtonian fluid. The properties of the fluid are assumed constant except change of density with temperature during buoyancy. Hence, the Boussinesq approximation is employed (Ridouane *et al.*, 2005).

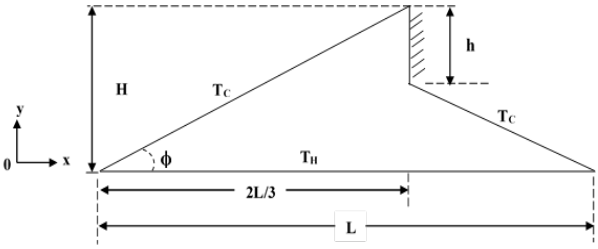


Figure 1. Physical Model

There is no internal heat generation in the cavity and all its walls are impermeable. The flow and thermal fields are taken to be steady. Since the size of a real life roof and thermal conditions of the environment vary, the computational domain dimensions and boundary conditions are normalised. The equations governing the steady, laminar natural convective flow and heat transfer are expressed in dimensionless form, with Boussinesq approximation, as:

Continuity:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (1)$$

X-Momentum:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \quad (2)$$

Y-Momentum:

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+RaPr\theta \quad (3)$$

Energy:

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \quad (4)$$

where

$X=\frac{x}{L}, Y=\frac{y}{L}, V=\frac{vL}{\alpha}, U=\frac{uL}{\alpha}, \theta=\frac{T-T_C}{T_{H-}T_C}$,

$P=\frac{pL^2}{\rho\alpha^2}$, $Pr=\frac{\nu}{\alpha}$, and $Ra=\frac{g\beta(T_H-T_C)H^3}{\alpha\nu}$.

The boundary conditions are:

Velocity:

$U = V = 0$ *(no slip condition along the walls)*

Temperature:

$\theta = 1$ *(isothermal hot ceiling)*
$\theta = 0$ (isothermal cold inclined walls)
$d\theta/dx = 0$ *(adiabatic vertical wall)*

Roof pitch angles of 14°, 20°, 25°, and 35° that are common and within the standard roof pitch range were studied. The parametric details are as stated in Table 1.

Table 1: Parametric Details of the Enclosures

Pitch Angle (ϕ)	14°	18°	30°	45°
Aspect Ratio (*AR*)	0.25	0.325	0.58	1.00
Rayleigh Number (*Ra*)	3×10^5	7×10^5	4×10^6	2×10^7

Figure 2. Computational Grid for the 30º - Pitch Enclosure

Fine unstructured triangular meshes, shown in Figure 2 for the 30º pitch enclosure, were used for the computational domains. The finite-volume based ANSYS FLUENT© CFD package was used to solve numerically the coupled nonlinear partial differential equations (1) - (4) governing the natural convective heat transfer problem. The pressure-velocity coupling in the equations was resolved by the SIMPLE algorithm. The QUICK scheme in the software was employed to spatially discretise the momentum and energy equations. PRESTO scheme was used for the pressure interpolation. The conservation equations were solved iteratively till convergence was achieved. The convergence criterion for the continuity equation was set at 10^{-5} while that for the momentum and energy equations was set at 10^{-7}. To ensure the accuracy of the solution scheme and to determine an appropriate grid density, a grid independence test was carried out using the value of the average Nusselt number of the hot base wall relative to the number of elements. The outcome of some of the numerical runs is as shown in Table 2 for the 14^0-pitch enclosure.

Table 2. Grid Independence Test for the 14° - Pitch Enclosure

Number of elements	45,255	50,373	55,895	61,215
$\overline{Nu}$	16.45	19.75	22.32	22.46

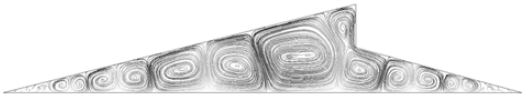
Ability of the commercial CFD package used to effectively carry out the computation of the present study is premised on the work of Yesiloz and Aydin (2013). They compared the results of the numerical analysis of laminar natural convection in a right-angled triangular enclosure heated from below carried out using ANSYS FLUENT with the results of an experiment with the same configuration and Rayleigh number range of 10^3 to 10^7. The results are found to be in good agreement.

3. Results and Discussion

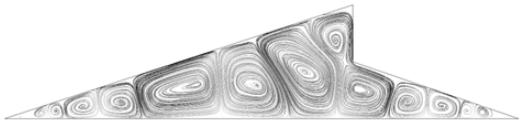
The steady state results obtained for the fluid flow and heat transfer within the enclosures are presented in Figures 3-8. These include the streamlines, contour plots of the velocity and temperature, and the graphical plots of the variations of the velocity and temperature across some sections. Others are the graphical plot of the mean Nusselt number variation along the hot base wall. The reference velocity is $U = \sqrt{g\beta(T_H - T_C)H}$ and the dimensionless temperature, $= {(T - T_C)}/{(T_H - T_C)}$; hence both range from zero to one. The length, L of the base wall and the enclosure height H scale the x-coordinate and y-coordinate, respectively.

3.1 Thermal and Flow Fields

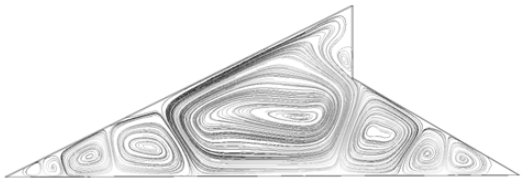
The thermophysical structure of the system is depicted by hot, less-dense air that rises in form of a plume from the heated base wall through the attic and hits an upper inclined cold wall. In reaction to the buoyant force, the upward flow bifurcates in either direction along the inclined wall. After losing part of its heat content, the fluid becomes denser. Consequently, the flow, under gravity, detaches from the inclined wall, goes down to the base wall to regain heat and repeat the process. The size, strength and direction of rotation of the cells are determined by the plume's location and the buoyant force propelling it. The vertical wall distorts the flow field around it and, in some cases, caused flow detachment. Also, the lengths and the difference in the subtending angles of the cold inclined walls affect the rate of heat exchange with the hot horizontal base wall thereby making the cell arrangement asymmetric. The temperature fields are strongly influenced by the airflow patterns in the enclosures.



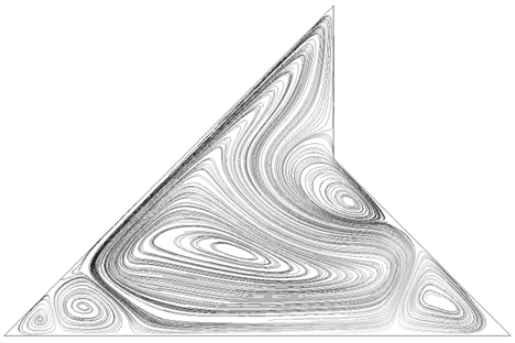
(a) 14º



(b) 18º



(c) 30º



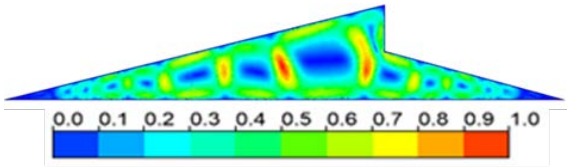
(d) 45º

Figure 3. Streamlines for Different Pitch Angles

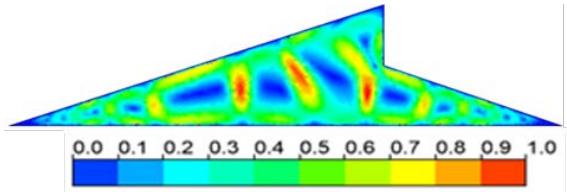
In Figure 3a for the 14^0-pitch enclosure, the flowfield shows ten counter-rotating cells that are asymmetrically arranged; six on the left and four on the right. The size and strength of the cells reduce from the midsection to the bottom corners. Upon hitting the vertical wall, the plume rises directly below it splits. A flow detachment occurs. As a result, a secondary, weak-strength, clockwise-rotating cell is formed at the upper corner. At the bottom corners, the nearness of the hot and cold walls makes conduction to dominate; the area becomes smaller with increasing roof pitch angle. In the 18^0-pitch enclosure, Figure 3b, due to a marginally increased space area, the airflow structure remains practically unchanged but the cells have become bigger.

In the 30^0 pitch enclosure, Figure 3c, some of the cells have merged, leaving only seven. Three cells at the midsection merged with the one at the upper vertex to form a big vortex that is distorted by the vertical wall. The central cell rotating anti-clockwise became the main force in the flow as it drags down cold air along almost half of the left inclined wall. In Figure 3d, with more space to roam in the 45°-pitch enclosure, the large central vortex appears to have 'swallowed up' more cells. Others cells have also grown larger and have gained higher convective strengths. In each of the enclosures, the rotating speed of a cell reduces with the cell size. The multi-cellular flow pattern obtained in this study concurs with the results of Cui *et al*. (2015 and 2019). It is also similar to that reported in the experiments conducted in an isosceles triangular enclosure heated from the base wall by Holtzman *et al.* (2000).

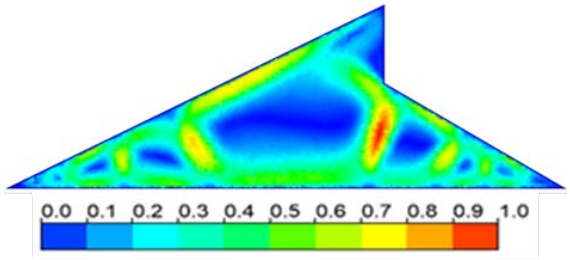
Figure 4 shows the contour plots of the air velocity for each of the enclosures. In each cell, there are two main regions: the outer and core regions. In the outer region which falls around the periphery of a cell's circumference, the values of velocity are relatively high. On the other hand, the core region is somehow quiescent. The velocity values are also high along the plumes, in between adjacent cells and along the walls.



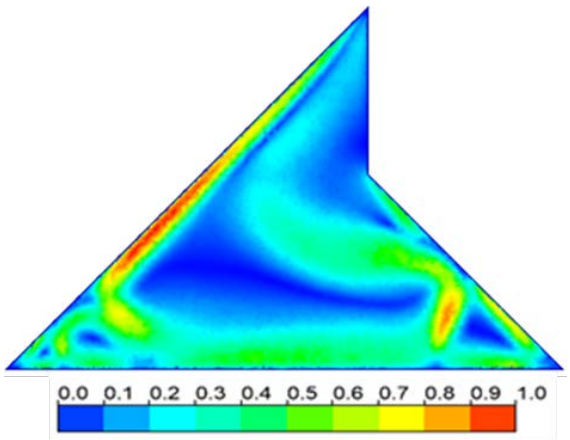
(a) 14°



(b) 18°



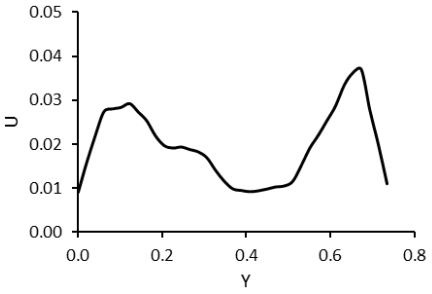
(c) 30°



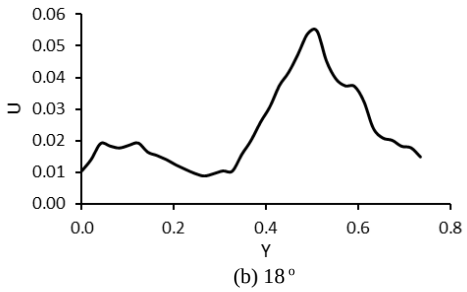
(d) 45°

Figure 4. Velocity Contour Plots for Different Pitch Angles

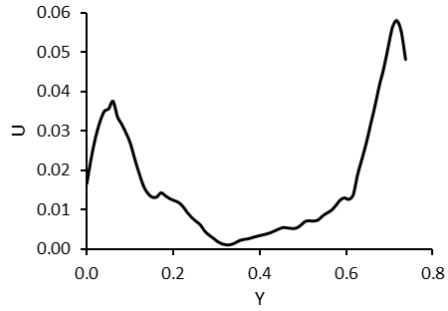
In Figure 5, the variation of the values of air velocity along the vertical cross-section at X = 0.5L is presented for the roof pitch enclosures. The profiles show air velocity at the part of the cells that falls on the wall. The vertical line at X = 0.5L passes through the largest cell in all the enclosures. The velocity is relatively high at the edge of the cell and low at the core. The higher the roof pitch, the higher the velocity of rotation.



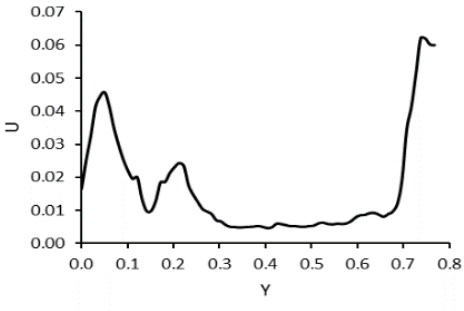
(a) 14°



(b) 18°



(c) 30 °

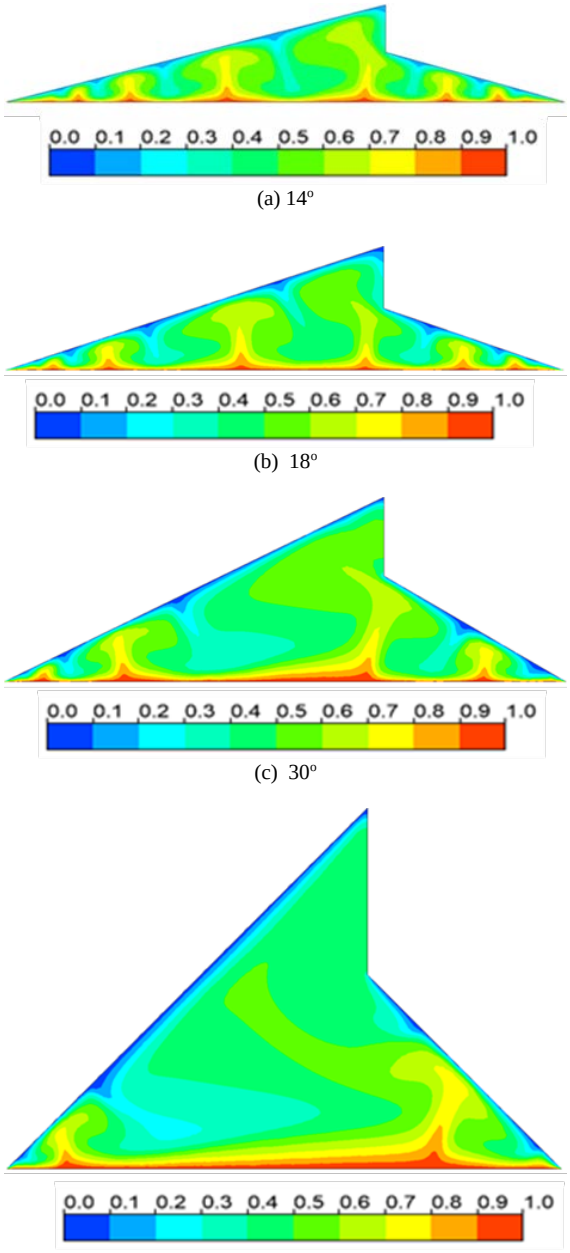


(d) 45 °

Figure 5. Air Velocity along Vertical *X*=0.5L Cross-section of Each Enclosure

Figure 6 shows the contour plots of the temperature distribution within the enclosures. The thermal field is characterised by rising hot plumes from the heated base wall and of cold jets descending from the cold upper walls. The system results in a mixture of hot and cold air within the attics. A plume and a jet fall between two counter-rotating cells. Due to the peculiar shape of the enclosure, the thermal field is strongly influenced by the strength of the convection currents and the distortion of the airflow by the vertical wall. The development of plumes in this study is in consonant with the report of Cui et al., (2015). In the 14^0 roof pitch enclosure, Figure 6a, the high number of counter-rotating cells leads to thorough mixing of air. As the pitch angle increases however, the volume of cold air that is being heated by the same base wall length becomes larger. Hence, the heating effect and thus the average temperature across the enclosure reduce. In all but the 45^0 pitch enclosure, the vertical wall falls on the path of a plume of hot air, hence, being constantly heated. Therefore, whether used as a penthouse window or a skylight, the warm vertical wall reduces snow thickness on it.

The temperature profiles along the vertical cross-section at X= 0.5L are presented in Figure 7 for each enclosure. The variation of the temperature values follows the part of a cell that falls along the lines. The plots clearly show the thermal boundary layers along the base wall (at Y = 0) and the opposing inclined wall. For each of the vertical cross-section, the thickness of the boundary layer reduces as the roof pitch increases.



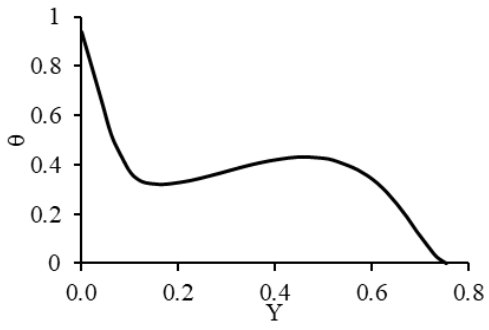
(a) 14°

(b) 18°

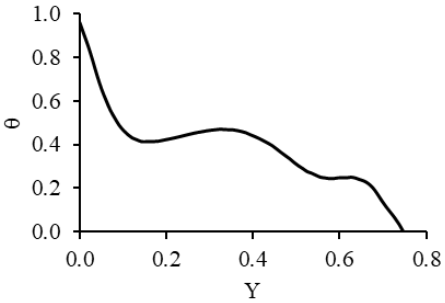
(c) 30°

(d) 45°

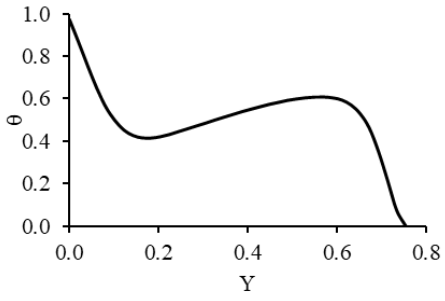
Figure 6. Temperature Contour Plots for Different Pitch Angles



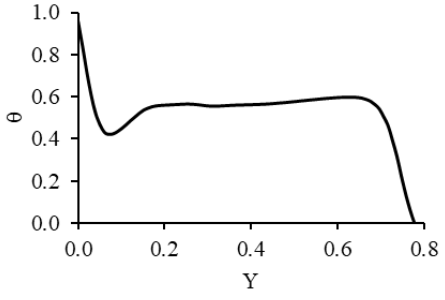
(a) 14 °



(b) 18 °



(c) 30 °



(d) 45 °

Figure 7. Temperature along vertical *X*=0.5L cross-section of each enclosure

3.2 Heat Transfer

The rate of the flow of heat from the hot base wall into the air-filled attic can be represented by the average heat transfer rate over the hot base wall depicted by the mean Nusselt number defined as,

$$\overline{Nu} = \frac{\bar{q}\, L}{k_f\, \Delta T} \qquad (5)$$

where $\bar{q}$ is the mean value of the local surface heat flux across *L*. The plot of the mean Nusselt number ($\overline{Nu}$) of the hot basewall against the Rayleigh number (*Ra)* for the 14° roof pitch enclosure is presented in Figure 8 where $\overline{Nu}$ increases with Ra. This agrees with literature on the subject (Cui et al., 2019).

The correlation between the $\overline{Nu}$ *and Ra* for the heat exchange along the hot wall of the 14° roof pitch enclosure is as indicated in Equation (6).

$$\overline{Nu} = 28.1\mathrm{Ra}^{0.232} \qquad (6)$$

The relation agrees closely with literature which suggests $\overline{Nu} \sim Ra^{1/4}$ for laminar flow cases. For the clerestory enclosure with roof pitch of 45^0 and *Ra* value of 2 x 10^7 in this study, the $\overline{Nu}$ value for the hot base wall is 34. At the same pitch angle and Ra of 10^7, Cui et al. (2019) got 32 for $\overline{Nu}$ for the hot base wall of a standard triangle.

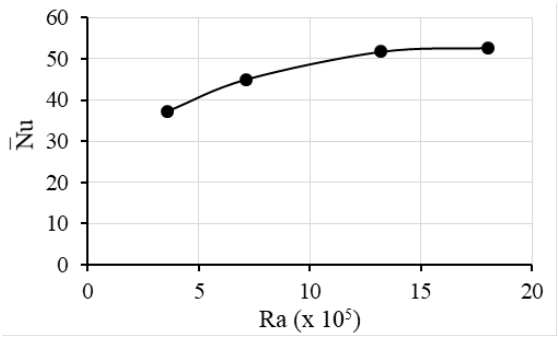


Figure 8: Mean Nusselt Number of the Base Wall against Rayleigh Number for 14^0-Pitch.

For the same *Ra* range, 5 x 10^7, Anderson *et al* (2010) obtained $\overline{Nu}$ value of 35 for the hot inclined wall of an isosceles triangular cavity. The implication of the results of this investigation is that, in temperate climate, heat loss across the ceiling into the roof can be minimised when the angle of the roof pitch is rather high. If roof of low-pitch is to be used, the ceiling insulation should be thick and of high quality.

4. Conclusion

A finite volume analysis of fluid flow and heat transfer in clerestory-shaped attics heated from below has been investigated. The shape of the enclosure has strong influence on the flow and temperature fields. As common to enclosures heated from the base wall, the flow field is characterised by counter-rotating vortices enclosed by aerodynamic boundary layers. The asymmetrically-arranged cells increase in number with the roof pitch angle. The size, strength and direction of rotation of the cells are controlled by the buoyant force propelling the thermal plumes from the bottom wall and the gravitational force on the cold jets from the top inclined walls. The reduction of the number and size of the counter-rotating cells and their formation within the enclosures provide an analogous reduction of the total heat transfer rate for increasing roof pitch. The temperature field is influenced by the flow pattern.

At low roof pitch angles, multi-cellular flow structure controls the transport processes within the enclosures leading to thorough mixing of air and hence, more uniform attic temperature. The values of velocity and temperature plotted across midheight and midlength of the enclosures displayed sinusoidal order. These profiles enable the prediction of suitable position for the placement of sensitive items on the rooftop. On the heat transfer, the correlation relating the mean Nusselt number and the Rayleigh number agrees with literature.

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Energy, Emissions and Exergy Analyses of Ethanol-Biodiesel-Coconut Oil Ternary Fuel Blends and Comparative Assessment of Their Performance in Compression Ignition Engines

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Abstract: *The demands on future energy conversion technologies are becoming increasingly stringent. Biofuels, which are considered to have a critical role in meeting growing energy needs, must find increasing avenues for compliance. Accordingly, ternary fuel blends have received significant attention because their physiochemical properties can be very similar to diesel, while overcoming some challenges associated with traditional biofuel use. Consequently, this work assesses the use of alcohol-biodiesel-vegetable oil blends in Compression Ignition (CI) engines. Three ethanol-biodiesel-vegetable oil blends were developed using 10%, 20% and 30% alcohol and their performances were compared to diesel and neat coconut oil. These blends were tested in a single cylinder diesel engine and their performances assessed using energy, emissions and exergy analyses. The results indicated that the blends had better brake thermal efficiency (BTE) values than diesel at high to medium loads, with the E30 blend having the highest BTE value of 31% at full load conditions as compared to 28.9% for diesel. The blends were also found to be comparable to diesel based on a First Law energy analysis. Additionally, it was found that the blends had better nitric oxides (NO) emission levels than diesel; at full load conditions, the E30 blend had the lowest value of 281 ppm as compared to diesel having a value of 299 ppm. However, they were found to have comparable levels for the other emissions characteristics that were examined. Further, the Second Law analyses indicated that the blends made better use of their fuel energy potential and thus, can be considered as a more suitable fuel for CI engine combustion. Collectively, the results suggest that the ternary blends are a viable candidate for future energy conversion via CI engines.*

Keywords: *Ternary blends; ethanol; coconut oil; CI engines; exergy analysis; alternative fuels*

1. Introduction

The role of energy in the advance of human civilisation is perhaps more critical than it has ever been. As the global population increases towards a projected 9 billion by 2050 and the economic prosperity of some nations continues to rise, the demand for increased energy utilisation is inevitable. At the same time, the increasingly evident impacts of changes in the global climate are presenting new challenges to many societies. In keeping with this, increased access to renewable and sustainable sources of energy with minimal emissions over their life cycles, are critical to meeting the growing global demand in a manner that minimises the rise in global surface temperatures. Concurrently, energy conservation and efficient energy utilisation are critical to keeping the growth of demand within manageable limits. Thus, technologies such as cogeneration, enhanced recovery and other methods that increase system efficiency are critical to ensuring that the maximum amount of available energy is extracted from a particular energy source.

Notwithstanding, the requirements for grid stability and dispatchability place further demands on energy conversion technologies. This must all be achieved in a manner that takes into consideration the existing energy architecture, identifying a transition pathway that is ultimately financially feasible. Consequently, the demands being placed on energy sources and their associated technologies, are perhaps more rigorous, multifaceted and stringent than ever before.

Biofuels have been identified by many as a potential energy source capable of contributing meaningfully to meeting the future of global energy demand. They are renewable with almost net zero emissions if implemented correctly. They can utilise existing energy architecture with little to no modification, making them more financially accessible and thus, easy transition pathways for many nations. Further, given their compatibility with existing energy conversion equipment such as IC engines and gas turbines, they easily meet the requirements for grid stability and for dispatchability. Thus, they make an excellent choice for base load power generation and can also complement non-dispatchable sources like wind and solar. Accordingly, the identification of suitable biofuel sources that perform sufficiently well with existing technologies and that have sufficiently available quantities, continues to be an area of much research.

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As first-generation biofuels, vegetable oils have long been considered as a substitute for diesel in power generation, particularly in internal combustion engines. Their relatively high calorific values, good lubricity and higher oxygen content than diesel, are favourable physiochemical properties for compression ignition (CI) engine performance. Accordingly, many investigators have examined the use of various vegetable oils in CI engines, and under varying conditions (Tippayawong and Wongsiriamnuay, 2002; Agarwal and Rajamanoharan, 2008; Haldar et al., 2008; Hellier et al., 2015; Haozhong et al., 2016). However, their use has been plagued by several issues such as gum formation, choking of injector nozzles, carbon deposit build-up, crankcase oil dilution and ring sticking to name a few (Ramadhas et al., 2004; Salmani et al., 2015). The literature provides many reviews which summarise their use in CI engines and details the key issues for consideration (Ramadhas et al., 2004; Corsini et al., 2015). Much of these issues continues to persist when neat vegetable oil biofuels are considered. In like manner, alcohols such as methanol and ethanol have also been considered as potential liquid biofuels. Their fast-burning rates, low viscosities and highly oxygenated nature, improve spray characteristics and usually facilitate good combustion in CI engines.

Further, their low cetane numbers and high latent heats of vaporisation cause a longer ignition delay and produce higher heat release rates and lower in-cylinder pressures, when compared with that of diesel (Zaharin et al., 2017). As such, many researchers have investigated their use via differing methods and yielding differing results (Mitchell et al., 1991; Seko and Kuroda, 1998, 2001). However, the general issues of low lubricity, low cetane number and lower calorific content, present significant challenges that must be overcome (Stone, 1999; Rossomando et al., 2017). Consequently, neat alcohol use in CI engines is usually discouraged.

Fuel blending is a common approach to addressing the challenges of neat vegetable oil and/or neat alcohol use in CI engines. It potentially leads to a fuel with enhanced physiochemical properties and can be more economical than other methods such as transesterification (Murray et al., 2019). Moreover, it potentially increases the quantities of suitable fuel available by incorporating fuel components that may be infeasible as standalone fuels. In keeping with this, much research has targeted the use of binary blends in CI engines. Blends of diesel and various vegetable oils have been thoroughly investigated and reported on.

In general, these blends have been found to exhibit better emissions than neat diesel but yield lower power outputs and lower efficiencies (Corsini et al., 2016; Haozhong et al., 2016; Che Mat et al., 2018). Similarly, binary blends of diesel and alcohols have also been investigated. These have generally led to higher efficiencies and better emissions than neat diesel. However, lower power outputs, higher fuel consumption and phase separation issues have challenged their suitability (Huang et al., 2004; Bayraktar, 2007; Yao et al., 2007; Sahin et al., 2015). In like manner, researchers have investigated the use of blends of diesel and biodiesel. These blends have been shown to have similar physiochemical properties to neat diesel (Kumar et al., 2016).

Like the blends of diesel and alcohols, these blends have led to better emissions and higher efficiencies; however, they have also led to lower BTEs and power outputs (Heidary et al., 2013; Habibullah et al., 2014; Siavash et al., 2015; Kumar et al., 2016; Ashok et al., 2018). Moreover, biodiesel addition in these binary blends has also been shown to decrease the rate of wear in engine components, due to its higher lubricity (Singh et al., 2018a 2018b). In the recorded instances of improved performance, the result has been attributed in large part to the highly oxygenated nature of the alcohol or biodiesel. The higher lubricity and lower viscosity of biodiesel have also been found to contribute positively to these effects (Senthil Kumar et al., 2003; Mistri et al., 2016; Agarwal et al., 2018; Patel et al., 2018). Lastly, several researchers have also examined the use of vegetable oil and alcohol blends. In almost all instances, alcohol addition has led to increases in brake thermal efficiency, specific fuel consumption and better emissions than both diesel and the neat vegetable oil (Senthil Kumar et al., 2003; Che Mat et al., 2018). However, power output was generally found to be lower than diesel and higher in specific fuel consumption.

Notwithstanding, researchers have reported some limitations with binary blends. Key among these are lower cetane numbers, higher viscosity and limited miscibility among the fuel components (Ali et al., 2016; Rossomando et al., 2017; Redel-Macias et al., 2017). More specifically, Shahir et al. have reviewed the work done on the use of diesel-biodiesel-ethanol blends (Shahir et al., 2015). They reported that a diesel–biodiesel– ethanol/bioethanol blend has improved physicochemical properties as compared to a diesel–biodiesel or diesel–ethanol/bioethanol blend separately. Redel-Macias et al. (2017) have also reported improvements in physiochemical properties for ethanol-castor oil-diesel blends, as compared to ethanol-diesel blends. Similarly, Hassan et al. have reported improvements in engine behaviour for diesel-biodiesel-butanol blends, as compared to a diesel-biodiesel blend (Hassan et al., 2018). These reports indicate that ternary blends have the capacity to yield better physiochemical properties and consequently, engine performance than binary blends. Accordingly, the research into ternary fuel blends is a current area of great focus (Atmanlı et al., 2014; Yang et al., 2016; Mofijur et al., 2016; Saleh and Selim, 2017; Prakash et al., 2018).

A review of the literature has revealed that the greater proportion of the investigation into the use of biofuels and their blends focus on an energy or first law analysis and not on an exergy analysis. As such, insight into the use of the biofuel is limited to open-system applicability and a more detailed understanding of the efficacy of energy

conversion and utilisation is not presented. In the instances where exergy analyses were conducted, the results sometime vary but often indicate favourable potential. Kul and Kahraman (2016) conducted energy and exergy analyses of biodiesel-diesel blends in CI engines. They found that the exergy associated with mechanical power output decreased while exergy destruction increased, as the percentage of biodiesel in the blend increased. However, though slightly lesser, the exergy associated with the exhaust gases was comparable to that of neat diesel. Other researchers have found similar results for the fuel blends examined (Panigrahi et al., 2016; Nazzal and Al Doury, 2019). Conversely, some researchers have reported on fuel blends with higher exergy efficiencies and even lower exergy destruction values than diesel, indicating a better utilisation of the inherent fuel energy (Reddy et al., 2018). Collectively, the literature suggests that the exact result of such analyses is highly dependent on the nature of the biofuel being examined.

To date, the approach to the development of ternary blends, usually involves the use of diesel as a blend component in order to achieve stability or attain specific fuel properties that are within an acceptable range. However, the work presented by the aforementioned researchers suggests that the development of ternary biofuel blends with vegetable oils and alcohols as key components are in fact possible. It suggests that such blends are likely to yield comparable physiochemical properties to diesel, overcome the issues associated with neat vegetable oil or alcohol use and potentially yield better engine performance. In light of this, this work develops an ethanol-biodiesel-vegetable oil ternary blend and examines its performance in a CI engine.

Varying blend constitutions are investigated and compared to neat diesel operation, in order to better understand the behaviour of this class of ternary blend. The work reports on the results of energy analyses, emissions analyses and exergy analyses for the various blends, thereby facilitating a more holistic assessment of the suitability of the blends for modern energy conversion arrangements. In doing so, this work seeks to provide insight into the suitability of these ternary blends and the wider technique of fuel blending, as a means of providing viable biofuel sources for future energy utilisation.

2. Materials and Methods

2.1 Blend Development

This work assessed the performance of three alcohol-biodiesel-vegetable oil blends. Coconut oil was used as the vegetable oil component in all blends tested during experimentation. The selection of coconut oil was primarily due to its availability. However, though coconut oil has a slightly higher cetane number than most other edible and inedible vegetable oil sources, its viscosity, density, flash point and heating value are all very similar (Baharak et al., 2016).

In the absence of any other distinguishing fuel properties and taking into account differences in calorific content, it is expected that the use of coconut oil will yield results that are indicative of other vegetable oils. Coconut oil was also trans-esterified with methanol to produce biodiesel and was used as a component in the blend. The coconut oil biodiesel (CME) was used both as a fuel component and a surfactant, facilitating mixing of the alcohol and vegetable oil components. Lastly, the alcohol used in experimentation was ethanol. Its selection was based on its known properties and reported combustion performance. Ethanol was obtained as a laboratory grade chemical, at a purity of 99.9%.

For the purposes of these tests, the ethanol was not obtained from bio-renewable sources due to limited availability. For each fuel test, 1.5 L of the respective blend was prepared and used over the entirety of the test. In all cases, the blends were produced by mechanical mixing of the blend components for a period of 3-4 minutes.

A total of five fuels were tested in this work. This comprised of three fuel blends, neat coconut oil and neat diesel. The blends that were tested were as follows: an E10 blend, an E20 blend and an E30 blend. By increasing the ethanol content gradually, the work sought to examine the impact of increasing ethanol proportion upon blend performance. The composition of each blend is given in Table 1. In general, 5% more biodiesel by volume than the alcohol percentage was used in the development of the blends. These relative proportions were found to produce more stable fuel blends based on previous work done (Murray and Wyse-Mason, 2018).

Table 1. Composition of the Various Fuel Blends

Fuel blend	% Ethanol by volume	% Biodiesel by volume	% Coconut oil by volume
E10 blend	10	15	75
E20 blend	20	25	55
E30 blend	30	35	35

2.2 Engine Testing Procedure

In this work, the experimentation was conducted using a single cylinder, four-stroke, CI engine unit. The unit was developed for testing and its specifications are given in Table 2. All engine settings inclusive of throttle, fuel injection timing and fuel injection pressure, were kept constant during experimentation. The unit also contained a dynamometer, which was coupled to the engine and this allowed the engine load to be controlled. In addition, the unit was equipped with instrumentation which allowed for the measurement of air consumption, cooling water flow rate, temperatures and dynamometer force.

Exhaust gas temperatures were obtained by installing a thermocouple at the exhaust of the engine and engine speed measurements were taken from the engine shaft via a tachometer. Exhaust gas analyses were also conducted during experimentation. These comprised of two differing

measurements. The first involved the measurement of engine emissions using an Enerac 700AV exhaust gas analyser. The second measurement concerned the assessment of smoke concentration. Smoke concentration measurements were made using an Applus Autologic smoke meter, model 310-0432. Exhaust gas temperatures and all emission samples were taken end-of-pipe, before being safely vented to the atmosphere. Exhaust gas measurement units both utilised the probe approach and offered real time data monitoring and recording.

Table 2. Engine Specifications

Parameter	Value
Manufacturer	Plint Engineers (UK)
Bore/mm	87.3
Stroke/mm	110
Swept volume/cm^3	659
Compression ratio	16.5:1
Fuel injection pressure/ MPa	20 – 22.1
Fuel injection timing / degrees	24° before TDC
Rated speed /rpm	1800
Capacity /kW	7

The engine unit was retrofitted with a second fuel tank and all fuel blends were placed in this tank (see Figure 1). Conversely, the built-in fuel tank that was supplied by the unit's manufacturers was considered the primary tank and this was only used to store neat diesel. The process of experimentation began by filling the primary tank with neat diesel and then the secondary tank with the fuel blend to be examined. The unit was then started using neat diesel and allowed to run for ten minutes. The purpose of this initial period was to allow the engine to arrive at normal operating conditions and this was evidenced by the stability in the measured parameters.

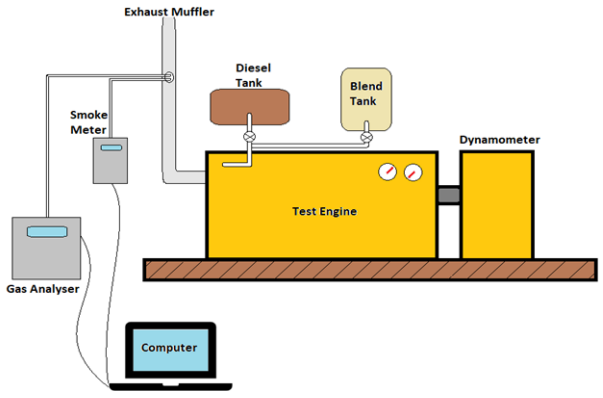

Figure 1. Schematic Diagram of Experimental Setup

Subsequently, the primary fuel tank was switched off and the secondary tank was switched on, allowing the engine to run using the fuel blend under consideration. The engine was then allowed to run for five minutes to arrive at fully developed conditions, using the fuel blend being tested. The various measurements were then recorded for six loading conditions, with the engine being allowed to achieve fully developed operational conditions each time the load was changed. All five fuels were tested using this procedure and the procedure was repeated for each fuel. The recorded engine parameters were subsequently used in the energy, emissions and exergy analyses.

2.3 Estimated Fuel Blend Properties

Given the prominent nature of the blend components and the standard mixing method used, homogenous blend theory was considered a suitable approach for estimating the blend properties in the absence of empirical equipment. This approach has been used by other researchers in similar circumstances and was proven to be very reliable (Atmanli et al., 2015; Rossomando et al., 2017). In keeping with this, the fuel properties of density, viscosity, cetane index and lower heating value (LHV) were estimated using Equations 1 through 4, respectively.

In Equations (1) to (4), b represents the calculated parameter for the blend; x represents the percentage volume of a blend component and i corresponds to a blend component.

$$\rho_b = \sum_{i=1}^{3}(x_i \rho_i) \quad (1)$$

$$\nu_b = \sum_{i=1}^{3}(x_i \nu_i) \quad (2)$$

$$CI_b = \sum_{i=1}^{3}(x_i CI_i) \quad (3)$$

$$LHV_b = \sum_{i=1}^{3}(x_i LHV_i) \quad (4)$$

$$\beta = 1 - \frac{a\varphi^b}{(t_{id})^c} \quad (5)$$

The properties for each blend component are presented in Table 3. Equation (5) was used to estimate the premixed burn fraction (β) for each blend, using the equivalence ratio (φ) and the ignition delay (t_{id}). The constants a, b and c were empirically determined and were specific to the engine studied, while φ and t_{id} were calculated based on other equations presented in Stone (1999). The estimated fuel properties are presented in Table 4.

Table 3. Fuel Properties for the Three Fuel Components of the Ternary Blends and Diesel

Fuel property	Ethanol	Biodiesel	Coconut oil	Diesel
Density (ρ) @ 15˚C (kg/m^3)	785	874.6	930	862.5
Viscosity (ν) @ 40°C (cst)	1.07	2.74	26.19	9.56
Cetane Index (CIn)	7	41	39	47
Lower Heating Value (LHV) (kJ/kg)	26,800	35,200	35,317	42,600

Table 4. Estimated Fuel Properties of the Ternary Blends

Fuel blend	Density (ρ) (kg/m^3)	Viscosity (ν) (cst)	Cetane Index (CIn)	Lower Heating Value (LHV) (kJ/kg)	Estimated Premixed Phase Burn Fraction (%)
E10	909.5	20.2	36.1	34562	9.63
E20	890.8	15.3	33.1	33780	11.7
E30	871.3	10.5	30.1	32961	13.9

2.4 Energy Analyses and Performance Assessments

The energy or First Law analyses were conducted to gain quantitative insight into the use and distribution of the energy delivered to the engine unit by the fuel. For the purposes of these analyses, the engine unit is considered as a control volume with the following assumptions:

- Standard conditions were evaluated at 1 atmosphere (P_0) and 25°C (T_0).
- The engine unit operates at steady-state conditions.
- The combustion processes of all fuels tested can be modelled as complete combustion.
- Air is a gaseous mixture that consists of approximately 21% oxygen and 79% nitrogen.
- All gases in the system can be modelled as ideal gases.
- All liquids in the system can be modelled as incompressible liquids.

As a consequence, the energy interactions of the system were modelled and evaluated using Equation (6).

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e\right) \quad (6)$$

Further to this, the engine unit's performance was assessed using the performance indicators of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). Using the parameter data recorded during testing, these performance indicators were calculated using the following equations:

$$Brake\ power\ (BP) = BT * \omega \quad (7)$$

where *BT* is the brake torque measured from the dynamometer and *ω* is the engine operational speed.

$$BTE = {BP}/{(\dot{v} * \rho * LHV)} \quad (8)$$

where $\dot{v}$ is the fuel volume flow rate, ρ the fuel density and *LHV* the fuel's lower heating value.

$$BSFC = {\dot{m}}/{BP} \quad (9)$$

where $\dot{m}$ is the mass flow rate of the fuel.

2.5 Exergy Analyses

The exergy analyses were conducted to provide insight into the quality of energy utilisation and the efficacy of the combustion processes for the various fuels tested. The primary assumptions presented in the energy analyses of the previous sub-section, were also considered to be applicable for these analyses. In keeping with this, the exergy interactions for the system were modelled using Equation (10).

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i\, ex_{f,i} - \sum_e \dot{m}_e\, ex_{f,e} - \dot{E}x_d \quad (10)$$

The first summation term of Equation (10) represented the exergy associated with heat transfers. This was attributed to the heat losses to the cooling water. The second term was associated with the brake power output of the engine. Further, the last term of Equation (10) represented the exergy destruction rate.

The terms associated with the second and third summation signs of Equation (10) represented the flow exergy of the inlet and outlet streams respectively. The flow exergy ex_f is more completely represented by Equation (11). Further, the chemical exergy component ex^{ch} of Equation (11) was determined using Equation (12) if the stream consisted of a fuel, or via Equation (14) if it consisted of a gas or gaseous mixture. In instances where the stream consisted of a fuel, Equation (12) was evaluated using Equation (13), where *h*, *c*, *o* and *α* represented the mass fractions of hydrogen, carbon, oxygen and sulphur in the fuel, respectively (Kul and Kahraman, 2016; Nazzal and Al Doury, 2019). For Equation (14), the chemical exergy was evaluated on a molar basis where y_k represented the mole fraction of the kth component in the mixture at standard conditions, while y_k^e represented it in the environment (Moran and Shapiro, 2000).

$$ex_f = (h - h_0) - T_0(s - s_0) + \frac{v^2}{2} + gz + ex^{ch} \quad (11)$$

$$ex_{fuel}^{ch} = LHV\varphi \quad (12)$$

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}\left(1 - 2.0628\frac{h}{c}\right) \quad (13)$$

$$\overline{ex}_k^{ch} = \bar{R}T_0 \sum_k y_k \ln\left(\frac{y_k}{y_k^e}\right) \quad (14)$$

3. Results and Discussion

3.1 Engine Performance Assessment and Energy Analyses

Figures 2 presents the brake thermal efficiency (BTE) results for the five fuels tested. As shown, the highest BTE value recorded at full load was for the E30 blend. This was an average value of 0.312 and had a variation of 2.5% between values. Conversely, the lowest BTE value at full load was recorded for neat coconut oil. It had an average value of 0.272 and a variation of 6.3% between values. In general, the average values recorded for all fuels at the various load conditions, showed variations of less than 5% between the two trials. Coconut oil was the only exception to this, with a maximum variation of approximately 10% at the 20% load condition. Thus, the results generally demonstrated good consistency.

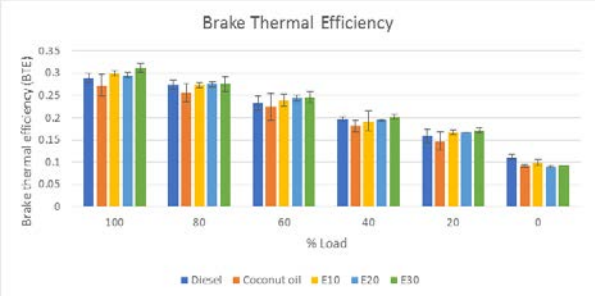

Figure 2. Brake Thermal Efficiency Values for the Five Fuels tested

Of the various trends noted from Figure 2, perhaps the most interesting is the higher BTE values associated with the fuel blends. All three fuel blends yielded higher BTE values than diesel at the 100%, 80%, 60% and 20% load conditions, while the E30 blend also had a higher BTE value at 40% load. This is a welcomed result, as most of the ternary blends reported in literature generally yielded lower BTE values than neat diesel. More importantly however, this result indicates that more of the fuel energy of the ternary blends is being converted or used for brake power. Thus, the blends can be considered to be more efficient than diesel in achieving the goal of generating brake power. This result is likely a consequence of differences in the combustion processes due to the presence of the alcohol in the ternary blends and will be further explored in the subsequent sections.

The second notable trend concerns the variation in BTE values among the three blends. In general, it was found that BTE increased with alcohol addition across all load conditions. Thus, the E30 blend generally had the highest BTE values, while the lowest of the three was recorded for the E10 blend. Once more, this result points to the significance and role of ethanol in the ternary blend's combustion process. Conversely, the low BTE values for neat coconut oil can be attributed to the issues previously discussed in the literature review, such as higher viscosity and poorer atomisation.

Figure 3 shows a reversed trend to that seen in Figure 2. Here, the lowest specific fuel consumption (SFC) value recorded at full load conditions was for neat diesel. It was an average of 0.293 kg/kWh, with a 2.5% variation between recorded values. In keeping with this, the highest SFC value at full load was recorded for neat coconut oil. This was an average value of 0.375 kg/kWh, with a variation of 6% between recorded values. These results are a consequence of the lower LHVs of neat coconut oil and of the ternary blends as estimated in Table 4. The lower values mean that larger masses of fuel must be consumed in order to produce similar power outputs to neat diesel.

Though all ternary blends have higher BSFC values than diesel, their values are all lower than neat coconut oil, except at the no load condition. This occurs despite the fact that the LHVs of all ternary blends are lower than that of neat coconut oil. This result is a consequence of the higher BTE values of the ternary blends. More specifically, the higher BTE values mean that more of the fuel energy is used and consequently, this decreases the mass of the ternary blend required to achieve the same brake power. With the exception of the no load condition, it would be noted that the BSFC values of the three blends show very little difference. However, both calorific value and density decrease with ethanol addition. Consequently, the general similarity in BSFC values can be attributable to the increasing BTE with ethanol addition.

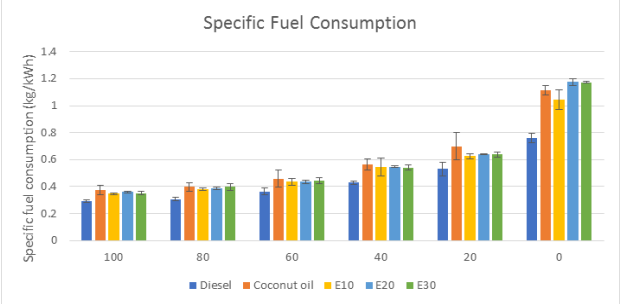

Figure 3. Specific Fuel Consumption Values for the Five Fuels Tested

From an operational standpoint, it is crucial to note that the higher BSFC values for the blends are also somewhat counterbalanced by their increased density. This effect however, decreases with increasing ethanol content. Together, the counterbalancing effects of increased BTE and increased density, mean that though BSFC increases for the blends the actual volume of fuel consumed may not vary significantly from that of diesel for blends of lower alcohol content. However, blends of higher alcohol content are likely to see some increases in volume consumption. Volume consumption can potentially be equivalent to diesel depending on blend constitution. Accordingly, a balance must be found. Given that liquid fuels are often traded on the basis of volume, this is a factor that must be carefully considered.

Figure 4 shows the First Law energy distribution for the five fuels at the full load condition. Given the differences in energy content among the various fuels, the evaluation is conducted on a percentage basis to facilitate better comparisons and a more insightful assessment.

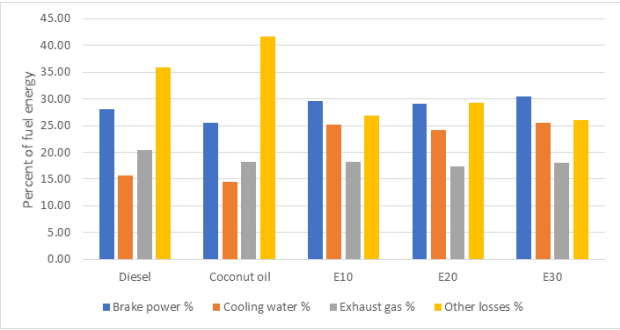

Figure 4. First Law Energy Distribution for All Fuels at Full Load Condition

The first noticeable result is that the E30 blend shows the highest percentage of fuel energy being used for break power generation. This is consistent with the BTE results discussed previously. Another trend of significance concerns the percentage of energy retained by the exhaust gases. It would be noted that the highest level of energy retention in the exhaust gases, is reported for neat diesel operation. This was also found to be true for all load conditions. Thus, with respect to the use of exhaust gases for further energy applications, diesel fuel operation is most suitable. The lowest percentage energy retention in the exhaust gases was recorded for the E20 blend. Further, all blends were also found to have lower percentages of energy in the exhaust gases than neat coconut oil. Nevertheless, these differences are generally between 2-3% and suggest that the exhaust from the ternary blends can likely be put to use for scavenging or cogeneration processes in a similar manner to diesel but are likely to be less efficient.

A consideration of the cooling water and other losses energy distributions, points to key differences between the combustion processes of the ternary blends and that of diesel or neat coconut oil. Firstly, the highest level of other losses is recorded for neat diesel at approximately 41.7%. This is only slightly lower for diesel. However, it is significantly lower for all ternary blends. Conversely, the lowest level of energy losses via the cooling water is reported for neat coconut oil, while the highest levels are reported for the blends. Moreover, the distribution of energy between the cooling water and other losses, is generally equal for all blends but not for neat diesel or coconut oil operation. However, though the results point to some underlying differences in the energy utilisation processes, an exact reason based solely on a First Law analysis is unclear.

3.2 Characteristics of the Emissions

Four exhaust gases and smoke concentration were assessed for all of the fuels examined. For each parameter, the data obtained from the analysers was further statistically assessed to determine its statistical significance. This assessment involved conducting pairwise comparisons of each fuel against the other, using a 95% confidence interval. The assessments were done using the Microsoft Excel, Analysis ToolPak solver add-in. The analyses of the Carbon Monoxide and Dioxide (CO and CO_2) and Unburned Hydrocarbons (UHC) emissions generally yielded the same results, i.e., the emissions of all blends were found to be statistically comparable to that of diesel.

The nitric oxides (NO) emissions results for all fuels are presented in Figure 5. As shown, NO emissions decrease with load for all fuels. This is a consequence of the chemical reaction kinetics associated with NO formation. NO and nitrogen oxides (NOx) formation are known to be influenced by flame temperature and flame speed; formation increases with increasing flame temperature and decreasing flame speed. In keeping with this, NO formation has been known to increase with decreasing engine speed. Thus, as engine speed increases with decreasing load, there is a decrease in NO emissions.

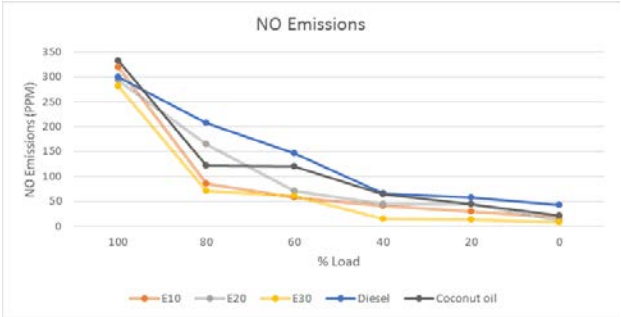

Figure 5. NO Emission Results for the Fuels Tested

Perhaps of greater interest is the comparative emission levels of the five fuels. Figure 5 shows that the highest levels of NO emissions are recorded for diesel and neat coconut oil. This is confirmed by the statistical analyses, which found all of the fuel blends with the exception of the E10 blend, to be significantly lower than diesel. The E10 blend was found to have comparable performance to diesel. In general, the decrease in the NO emissions associated with the blends is likely a direct consequence of the alcohol's high heat of vaporisation and is well documented in the literature. The higher heat of vaporisation of ethanol leads to lower in-cylinder temperatures than diesel during combustion. This in turn negatively affects the thermal mechanism of nitric oxide formation as described by the extended Zeldovich mechanism, resulting in lower NO emissions. This represents a clear advantage in the use of the ternary blends as compared to the use of diesel.

Figure 6 shows the smoke concentration measurements for all of the fuels tested. It shows a general trend for all fuels where smoke concentration decreases around mid-load but rises again to its initial levels at the lower loads. The lowest smoke concentration levels were recorded for the E30 blend and for diesel. The statistical analyses confirm that diesel was found to be less than the E10 and E20 blends, while the E30 blend was found to have a comparative performance.

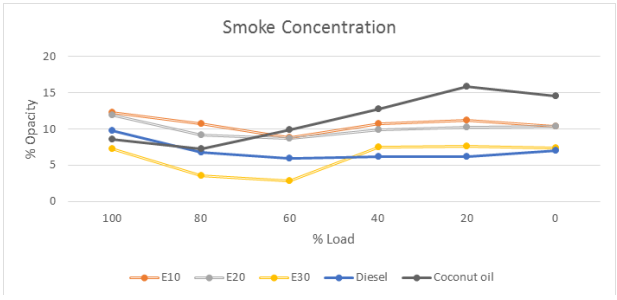

Figure 6. Smoke Concentration Measurements for the Fuels Tested

These results are a consequence of the alcohol concentration and its impact on the fuel blend's viscosity. Smoke concentration is known to be influenced by fuel viscosity. Fuels that are more viscous generally lead to poorer atomisation during injection; this in-turn leads to higher numbers of larger particles present in the exhaust. Accordingly, as alcohol concentration increases viscosity decreases and consequently, there is a decrease in smoke concentration. Alcohol addition is known to have this impact and other researchers have recorded similar decreases for the ternary blends examined. In like manner, the higher smoke concentrations recorded for neat coconut oil can be attributed to its higher viscosity.

3.3 Exergy Analyses

The results of the exergy analyses give insight into the quality of energy utilisation for each fuel. Critical to these analyses is an understanding that the total exergy of the input streams represents the maximum amount of work that can be obtained from the engine using a particular fuel. Here, the total exergy of the input streams is the sum of the fuel exergy and the exergy of the input air. However, the contribution of the input air to the total exergy is always less than 2% of the total. Thus, the total exergy is predominantly determined by the fuel stream. As the value of the total exergy varies for each fuel, a consequence of their varying LHVs, the analyses considered the percentage of the total exergy associated with different aspects of the engine's operation. Figure 7 shows the results of the exergy analyses for diesel fuel across all load conditions. The primary purpose of the exergy analyses in this work, was to facilitate a comparison of energy utilisation in each fuel. However, it is important to examine some key trends in exergy distribution with load variation for an individual fuel, as these trends help to further inform the comparison.

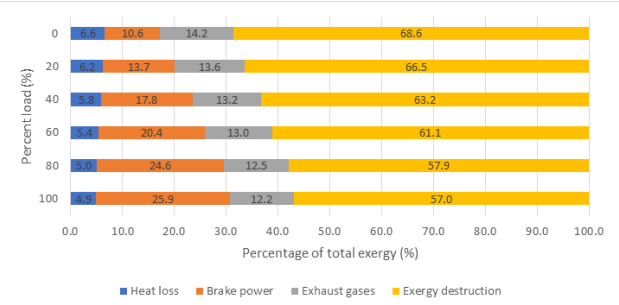

Figure 7. Exergy Distribution for Diesel Fuel at All Engine Load Conditions

The first of these trends concerns the brake power exergy. As can be seen from the figure, brake power exergy was found to decrease with decreasing load. This implies that a decreasing amount of the total fuel exergy is converted to brake power, as the load decreases. This was found to be the case for all fuels examined and is the reason for decreasing BTE with decreasing load. This trend has also been found by other researchers and is a standard feature of normal engine operation. Conversely, there is an increase in exergy destruction as the load decreases. This too is also a standard feature of engine operation and was observed for all fuels tested. However, the distribution of heat loss and exhaust gas exergies vary between the fuels, both in terms of quantities and rates of change. This will be discussed in the subsequent section.

Figure 8 shows the distribution of fuel exergy with respect to key engine operations, for all fuels at the full load condition. In considering these results, it must be recalled that engine combustion is an energy conversion process and providing that combustion is sufficiently complete, the final state is the same for all fuels. Therefore, the exergy analyses provide insight into how the energy of each distinct fuel is used as it moves towards a common final state. Accordingly, the percentage brake power exergy is of immediate interest.

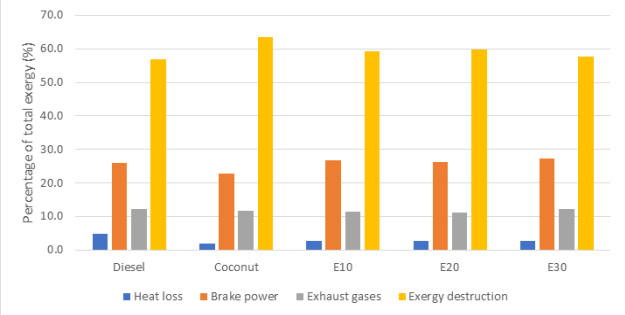

Figure 8. Exergy Distribution for the Various Fuels Tested at Full Load Conditions

It can be seen from the figure that the value for each of the ternary blends is higher than diesel. Further, this was also found to be generally true at the 80% and 60% load conditions. Conversely, at the lower load conditions diesel was generally found to have slightly higher values. The implication of this result is rather significant. It implies that the maximum work potential per unit mass of fuel is lower for the ternary blends than it is for diesel. However, despite being lower, the ternary blends are able to convert more of this potential to actual power output. Consequently, with respect to obtaining brake power, the ternary blends make better use of their lower energy contents than diesel does of its higher energy content. Accordingly, the ternary blends can be considered as a higher quality fuel, or as a fuel that is more suitable for generating power via CI engine combustion processes.

Further to the aforementioned result, it was found that the percentage exergy converted to brake power generally increased with increasing ethanol content across all loading conditions. This is the reason for increasing BTE with increasing alcohol content and can generally be attributed to the alcohol's role in the combustion process. The lower cetane numbers of alcohols cause longer

ignition delay periods at the start of combustion. As a consequence, there is a larger premixed phase in the cylinder when combustion begins. This is in keeping with the results of Table 4, which show an increase in premixed fraction for increasing ethanol content. Compounded with their fast-burning speeds, there are faster heat release rates and ultimately higher conversion of the fuel energy to brake power as a result of their addition. Accordingly, this result is more pronounced at higher engine loads where greater fuel volumes are injected into the cylinder. However, at lower engine loads the impact of this phenomenon decreases.

The results for the percentage exergy destruction show that the highest values are recorded for coconut oil. This was further observed to be true for all engine loads. Consequently, the lowest BTE values were also obtained for neat coconut oil as discussed previously and suggest that neat coconut oil is not the most suitable fuel for CI engine operation. Beyond this, it would be noted that the lowest exergy destruction percentages were recorded for diesel and this was also found to be true at all loads.

The percentage exergy destruction for the ternary blends, though lower is comparable to that of diesel at full load. In particular, the E30 blend is higher by only 0.7%. This indicates that although more of the energy potential of the ternary blends is converted into brake power than for diesel, more of this potential is also destroyed. Further, it was found that the percentage of exergy destruction for the blends increased more quickly with increasing load than in the case of diesel operation. This can also be attributed to the impact of the alcohol and its effect of increasing ignition delay. It has been reported by other researchers (Nazzal and Al Doury, 2019) that increasing ignition delay increases the rate of exergy destruction. This would therefore account for the aforementioned result and partially for the increase in exergy destruction with decreasing load, as ignition delay also increases with decreasing load. Consequently, the impact of alcohol addition on the ternary blends simultaneously increases energy conversion to brake power, while increasing exergy destruction.

As shown in Figure 8, the highest recorded exhaust exergy percentage is for diesel. It would be noted however that the exergy allocated to the exhaust gases for all ternary blends is generally similar. As load decreases however, it was found that the exergy allocated to the exhaust gases increases slightly in diesel but not significantly for the ternary blends. Taking into consideration the results of the energy analyses, the quality of the energy in the exhaust gases is comparable for both diesel and the ternary blends. Considering the quantitative differences, both can be used for further applications where possible. However, this is likely to be more efficient for diesel operation.

Regarding the distribution of exergy to the cooling water, results show that a greater percentage of the fuel exergy is transferred away via heat losses, for diesel than for the ternary blends. This result holds true for all load conditions. This is a consequence of the lower in-cylinder temperatures associated with alcohol-based combustion. Lower temperatures result in lower heat transfer rates to the cooling water and the environment.

Given the increased exergy destruction percentages for the ternary blends when compared to diesel, the differences in brake power exergy are generally accounted for by variation in either exhaust gas exergy or heat loss exergy distribution. At the higher load conditions, the ternary blends appear to better utilise the fuel exergy that would be otherwise lost to the exhaust gases or the cooling water, by converting it to brake power. As a consequence, the energy lost to the cooling water in the ternary blends is of a lower quality to that of diesel, though it may be quantitatively larger. This explains the better energy utilisation processes of the blends and their greater suitability for CI engine combustion.

5. Conclusion

This work examined an alcohol-vegetable oil ternary blend and compared its performance to that of diesel in a CI engine. It assessed three configurations of the ethanol-biodiesel-coconut oil blend by conducting energy, emissions and exergy analyses. The results support the findings that blending can improve the physiochemical properties and consequently engine performance of neat vegetable oil. The results indicate that the ternary biofuel blend potentially not only matches the performance of diesel in a CI engine but in some ways surpasses it.

The following points regarding the performance of the ternary biofuel blend were noted, below:

- In the fuel blends between 1-2% more of the inherent energy content is used in the generation of useful power output at full load conditions, when compared to diesel. Approximately 6.5-10% more of the inherent fuel content of diesel is unrecoverable due to losses, as compared to the fuel blends. Based on a First Law analysis, the blends can be considered to be a more efficient fuel than diesel at higher loads, as more of the fuel energy is directed towards achieving the goal of generating brake power.
- The blends have higher BSFCs than diesel. However, this is offset by their higher BTEs and higher densities. At full load conditions, the blends were found to lead to an increase in BTE of at least 0.6%, with the E30 blend has a higher BTE by more than 2%. Thus, the collective effect is to make them comparable to diesel in general operation.
- The blends have better NO emission levels than diesel at all load conditions, with the E30 blend having a lower emission level by approximately 20 ppm at full load. The emission levels of diesel and the fuel blends are comparable with respect to other exhaust gases.
- Based on a Second Law analysis, the blends were found to better utilise their inherent work potential than diesel, at higher to medium load conditions, as

best seen in the E30 blend. Approximately 1.5% more of its work potential is converted into useful output, as compared to neat diesel at full load conditions. They can be considered as a better quality or more suitable fuel for CI engine operation.

To conclude, the ethanol-biodiesel-coconut oil blend can potentially serve as a replacement for diesel in a CI engine and can meaningfully contribute to the future of energy conversion.

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Dominating Factors of Road Failures: Perceptions of Key Stakeholders in the Small Island Developing State of Trinidad and Tobago

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Abstract: *Accelerated global population increase, socioeconomic and environmental changes have resulted in spiralling maintenance costs for pavements. Current understanding of pavement deterioration fails to address this longstanding issue, and Small Island Developing States (SIDS) are not immune to the recurring expense incurred from pavement degradation. Existing academic debates on design and construction inadequacies in pavement longevity do not address regular maintenance challenges. This research examines the reasons for frequent pavement failures and explains how they affect Trinidad and Tobago's future maintenance and economic development. A questionnaire was completed by 120 contractors, consultants, and state agency experts specialising in road construction and maintenance. The findings revealed from an assessment of the Relative Importance Index (RII) that utility cuts by the Water and Sewerage Authority were the most important (0.904), followed by maintenance culture (0.898), quality of work (workmanship) (0.888), poor drainage facilities, and overloaded vehicles (0.854). Climate change (temperature) was the lowest-ranked cause overall (0.568). The findings also show that economic growth and development are directly and indirectly affected, resulting in high vehicle running costs, longer travel times, and higher prices for fundamental products and services. Recommendations are made to aid engineers and policymakers in identifying critical causes and reducing the adverse consequences of frequent pavement failure.*

Keywords: *Maintenance, Pavement deterioration, Perceptions, Road failures, Trinidad and Tobago*

1. Introduction

Pavement Infrastructure is an important asset that is critical to the socio-economic development of developing countries. Over time, all pavement infrastructure will gradually deteriorate because they are all designed and constructed with an expected service life. Therefore, it will be in the best interest of road agencies to provide continuous assessment and maintenance of their road network, to keep them in a safe and functional condition. Failures to maintain pavement infrastructure, as described by Harral and Faiz (1988), can be considered equivalent to the act of disinvestment, as it suggests that the sacrifice made prior has been wasted. Pavement deterioration processes occur because of structural fatigue, and functional distresses. When these distresses become more prevalent, timely and adequate maintenance is required. However, if timely maintenance is neglected, improperly executed, or delayed, it results in further deterioration and consequently affects the travelling public's safety. Additionally, it also contributes to the riding quality, serviceability and the cost associated with future maintenance and rehabilitation (M&R) strategies (Zumrawi 2015).

Banda (2018) stressed that the deterioration of flexible pavements is increasing much quicker than the supporting maintenance budgets and institutional limits, thus, adversely affecting wealth generation and development. From a safety perspective, poor road conditions increase the severity of multiple-vehicle accidents on all roads (Lee et al., 2015). Research conducted by Pais et al. (2013) and Raheel et al. (2018) showed that traffic and axle loadings have increased and frequently surpassed existing roads' design limits. New pavements, if insufficiently maintained, will deteriorate quickly within the first half of their service life (Markow, 1990; Visintine et al., 2016).

Roads, and means of transport, make a crucial contribution to economic development and growth and bring important social benefits. Poorly maintained roads

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constrain mobility, significantly raise vehicle operating costs, increase accident rates and associated human and property costs, and aggravate isolation, poverty, poor health, and illiteracy in rural communities (Burningham and Stankevich, 2005). Failure to provide adequate road maintenance is the main reason for the lack of sustainable road transport networks in many countries (Gwilliam and Shalizi, 1996). Delaying or postponing road maintenance results in high direct and indirect costs. Neglected roads will progressively become more difficult to use, resulting in increased vehicle operating costs, more frequent repairs, increased fuel use, and the hesitancy of transport operators to use the roads. These effects impose a substantial burden on the economy: as passenger and freight services are truncated, there is a consequential loss of economic and social development opportunities (Burningham and Stankevich, 2005). The management and maintenance of a country's road network generate significant improvements in the general quality of transport provision, environmental, ecological, economic and technical sustainability aspects (Burrow et al., 2013).

Small Island Developing States (SIDS) are a collective group of countries that are mainly located in the Caribbean, Africa, Pacific, and the Indian Ocean regions (United Nations, 2022). They are relatively small in size and sparsely populated. Transportation networks in these states are critical assets that foster economic growth and development in key sectors such as tourism, agriculture, fisheries, and small-scale manufacturing activities. Dos Anjos Ribeiro Cordeiro et al. (2017) concluded that damage to any SIDS main transportation networks could potentially cripple their economic growth and hinder the effective transportation of goods and services around the islands.

Currently, there are 39 SIDS, in which the road network is often a large part of the country's infrastructure stock. Road sectors also often represent a substantial share of the government budget, especially for SIDS that do not rely heavily on international aid. While toll roads can partly finance road transport in many countries, SIDS faces significant challenges in attracting foreign direct investment and domestic private finance in road infrastructure. This means that road infrastructure maintenance, upgrading, and rehabilitation typically rely on public funds and international aid (Dos Anjos Ribeiro Cordeiro et al., 2017).

In an interview in April 2022, the Project Management Support Unit in the Ministry of Works and Transport (MOWT) in Trinidad and Tobago (T&T) indicated that the Programme for Upgrading Road Efficiency (PURE) agency under the MOWT, has spent TT$4.3 billion over the past decade on pavement maintenance and road rehabilitation projects to provide optimal service and ensure consistent road connectivity throughout the country. However, despite this effort, pavement deterioration seems to increase much faster than Trinidad and Tobago's corresponding maintenance budgets.

Previous research such as Shooshtarian et al. (2020), Pan and Pan (2020), and Zhao et al. (2016) revealed disparities in stakeholders' perceptions of construction-related activities. The number of stakeholders surveyed, according to these studies, limits the conclusions, generalisability, and application of perception research findings. Perceptions may be classified as subjective and variable across stakeholders due to elements such as fear, culture, education, society, connections, experiences, and knowledge (Zhao et al., 2016). These findings should be incorporated into the present stakeholder perception type research's conclusions and recommendations. This study focuses on identifying the causes of frequent pavement failure in Trinidad and Tobago (T&T) and how they impact economic growth, maintenance and rehabilitation strategies. The study's findings may help SIDs road agencies prioritise budget allocation, engage in focused research, and adopt initiatives to protect the nation's road network.

2. Road Infrastructure of Study Area

T&T is a Small Island Developing State in the Caribbean, with a land area of approximately 4,828 km2 and a population of 1.3 million. Due to the geographical location of the twin-island states, the country shares many common development challenges, such as economic isolation and limited resources, inclusive of the vulnerability to climate change and natural disasters. Despite the significant capital expenditure, a large portion of the road network is in poor condition, which indicates inefficiencies in the allocation and lack of road maintenance (Bollers et al., 2019).

For continuous stimulation of economic growth, the country heavily depends on its transportation and pavement network infrastructure by extension. Trinidad's entire road network is approximately 9,592km (5,960 miles) in length, including highways, main roads, and some secondary roads (MOWT, 2022). The country faces many challenges at the domestic level because the increasingly diversified economy requires an upgrade of the country's road infrastructure and internal connectivity to facilitate the growth of non-oil sectors such as agriculture and tourism (Oxford Business Group 2020).

In T&T, economic prospects are heavily underpinned by a single commodity, which is oil. The twin-island has produced more than three billion barrels of oil in the past century, making it the richest country in the Caribbean and the third-highest Gross Domestic Product (GDP) in the western hemisphere. Despite this, an increasing number of pavement infrastructures in the country are riddled with pavement defects, making some areas throughout the country impassable, which ultimately leads to vehicular damage (Seemungal, 2021). Moreover, since 2015 the energy sector has seen a fair share of problems with weak global energy prices and declining oil and gas production. As revenue associated with hydrocarbons has fallen in recent years, there has been a significant reduction in the

amount of government budgetary allocation to maintenance and road infrastructure development.

Consequently, this has created a view among many disgruntled citizens that most state agencies, such as the Municipal Corporations, Ministry of Works and Transport and Programme for Upgrading Road Efficiency (PURE), that are responsible for road construction, rehabilitation and maintenance, are disorganised and inefficient as it relates to the effective maintenance of roads in their respective networks and communities. Moreover, it has led to many reoccurring challenges, such as open protests by road users who openly express their dissatisfaction with the Ministry of Works and Transport as they complain about the poor road conditions of the secondary, residential and agricultural carriageways in their respective communities. These criticisms are prevalent notwithstanding provisions of $TT 2.5 billion for the roads and bridges sector, as part of the government's public investment programme, in the last four fiscal years. Funding for road construction and rehabilitation declined by 42 %, while funding for the 14 regional corporations for local government roads and bridges declined by 20 % from 2019 to fiscal 2021 (Seemungal 2021). These reductions in budgetary allocations for maintenance works will ultimately result in a number of selective roads not being properly maintained or receiving some form of deserved maintenance attention in a timely manner. Many of the roads under the purview of the local road agencies may further deteriorate into deplorable conditions over time.

3. Methodology

The objective of this study is to identify the causes of frequent pavement failure in Small Island Developing States with an emphasis on T&T. The perspectives of interest are those of the three main stakeholders of roadwork projects: state agencies, contractors and consultants.

3.1 Research Strategy

The study uses a deductive research design approach to incorporate simple mixed methods using an electronic survey with closed-ended and open-ended questions. Data collection was cross-sectional over a 3-month period. A population of 200 respondents was determined by those directly involved in the construction and maintenance of local roads. The population is comprised of relevant state agencies, such as the Ministry of Works and Transport, members of the Trinidad and Tobago Contractors' Association (TTCA), and members of the Construction Management Institute of Trinidad & Tobago (CoMITT).

3.2 Instrumentation

The survey instrument incorporated a five-point Likert-Type scale approach ranging from strongly disagree (1) to strongly agree (5), in which respondents were asked to provide feedback based on their experience. According to Nemoto and Beglar (2014), this approach allows respondents to freely choose options from multiple categories. The advantages of this method allowed the data to be gathered relatively quickly from many respondents. It also allowed the obtained data to be compared and combined with other qualitative data collection methods such as open-ended questions. The questionnaire is divided into four sections where:

Section 1 – Identifying the general profiles of the respondents by summarising their employment agency, position in their organisation, years of experience in the construction industry and the type of work executed by their organisation, such as new construction, maintenance and rehabilitation.

Section 2 – Listing their opinionated causes of frequent pavement failure and deterioration. A pilot test was conducted with 10 persons from 3 different agencies to review the 23 factors. These 23 factors were developed from a desktop study of published works from (Okigbo 2012, Tarawneh and Sarireh 2013; Pais et al. 2013; Zumrawi 2015; Adlinge and Gupta 2013; Burgess et al. 2010 and Tarawneh and Sarireh 2013). The pilot resulted in four additional factors that were included in the final survey.

Section 3 – Identifying the impacts of pavement failure on effective maintenance. This section entailed 11 closed-ended questions and six open-ended questions. The questions aimed to determine the impact poor pavement conditions have on maintenance works in T&T.

Section 4 – Identifying the impact of pavement deterioration on economic growth. This section consisted of 14 questions, which also involved open-ended and closed-ended questions. The aim of this section was geared toward ascertaining the effects pavement failure has on economic growth and wealth reaction in T&T.

3.3 Data Collection and Analysis

The electronically administered survey tool took place over a 3-month period achieving a response rate of 60% collectively which, according to Mugenda and Mugenda (1999), is considered adequate for data analysis and reporting. The quantitative data was analysed using the Relative Importance Index (RII) as shown in Equation 1. The RII is calculated for each of the indicators and ranked accordingly. The RII is derived to summarise the importance of each indicator. Each factor was ranked arithmetically within a range of 0-1, where a high RII value suggests a greater level of impact on each factor. Factors were then positioned in descending order based on this value to ascertain the most significant factor(s) affecting pavement maintenance failures in T&T.

$$RII = \sum W / (A \times N) \quad (1)$$

Where,

W = weighting as assigned on Likert's scale by each respondent in a range from 1 to 5, where 1 = no impacts, 2 = negligible impact, 3 = marginal impact, 4 = moderate

impact and 5 = major impact.
A = Highest weighting (here it is 5)
N =Total number in the sample / respondents

Qualitative content analysis is the classical method of analysing responses to open-ended questions since it can be employed both to gather information and to motivate respondents (Zull, 2016). According to Chambers and Chiang (2012), qualitative content analysis is a methodology that requires researchers who use it to make a strong case for the trustworthiness of the data. Every finding should be as trustworthy as possible, and the study must be evaluated concerning the procedures used to generate the findings. For this study, a categorisation scheme was developed for each open-ended question. Each question was tallied based on the assigned category, and each responded response was reviewed, evaluated, and summarised.

4. Analysis and Findings

4.1 Descriptive Characteristics of the Respondents

A total of 120 questionnaires were collected, of which 52% were professionals from state agencies, 31% were professionals from contractor firms, and the remaining 17% were from road and pavement consultant firms. Figure 1 shows the distributions of the respondents' positions in their respective organisations. Many of the respondents were positioned at the medium level of management, with the majority representing engineers, which account for 34%, project managers representing 26%, directors representing 17%, and construction managers representing 9%. Other junior positions accounted for 14%, collectively.

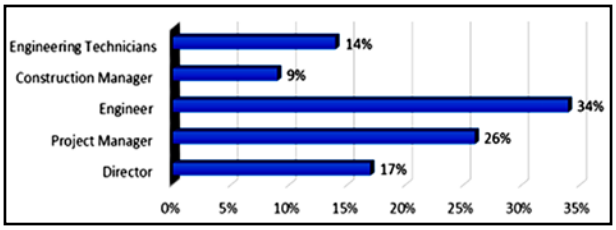

Figure 1. Respondents Current Position in Respective Organisations

As it relates to years of work experience in the related area of study, 10% of the respondents had entry-level to intermediate (<5 years) experience, as shown in Figure 2. Respondents with mid-level experiences (5-15 years) summed up to 51%, while the senior level experienced persons (>15 years) were 39%. The distribution of these experiences allowed for a balanced and holistic approach to the data collection.

Figure 3 highlights the type of work undertaken by the respondents identified in Figure 1. Persons involved in the new construction works of roads accounted for 87% of total study respondents. It is noted that respondents may be involved in more than one work-related activity. Although maintenance activities are part of the life cycle of road infrastructure, the result showed that it had the least amount (47%) of respondents' involvement in maintenance works or related projects. The remaining road infrastructure design and rehabilitation activities scored 49% and 64%, respectively.

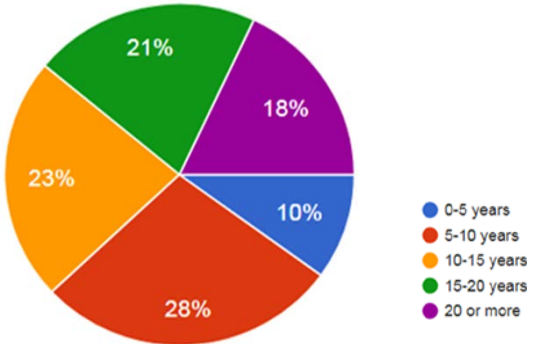

Figure 2. Respondents Experience

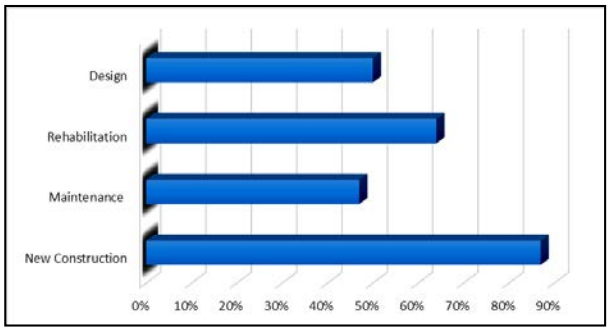

Figure 3. Type of Works Undertaken by Respondents

The statistical results suggest that the study population is sufficiently capable of identifying and addressing the factors of road failure based on the perception of persons involved in the design, construction and maintenance of roads. There is sufficient data that allowed a mixture of respondents from both the public and private sectors in the construction industry. Moreover, most of the respondents were positioned at the top and mid-levels of management within their respective organisations with sufficient experience and knowledge in the construction, maintenance, rehabilitation, and designs of pavement structures in T&T. Thus, the findings from this section give credence to the quality and validity of the research.

4.2 Perception of the Major Causes of Frequent Failures of Paved Roads

Table 1 provides the Relative Importance Index (RII) of the 27 factors and their respective ranks regarding the major causes of frequent failures of maintained roads in T&T. The five most critical factors are identified from the perspectives of respondents from state agencies, contractors and consultants. These are:

Table 1. Relative Importance Index (RII) and their rank

Cause of Pavement Failures	State Agencies		Contractor		Consultant		Combined Results	
	RII	**Rank**	RII	Rank	RII	Rank	RII	Rank
Utility cuts by W.A.S.A.	0.908	3	0.922	1	0.859	2	0.904	1
Maintenance Culture	0.919	1	0.884	2	0.859	2	0.898	2
Quality of Work (Workmanship)	0.912	2	0.865	3	0.859	2	0.888	3
Poor Drainage Facilities	0.865	5	0.865	3	0.847	3	0.862	4
Overloaded Vehicles	0.877	4	0.807	6	0.871	1	0.854	5
Quality of Design	0.808	9	0.826	5	0.800	6	0.812	6
Uncontrolled domestic water flowing into the road structure	0.812	8	0.774	8	0.835	4	0.804	7
Moisture (water)	0.839	6	0.755	10	0.729	10	0.794	8
Use of Poor-Quality Material	0.819	7	0.742	11	0.765	8	0.786	9
Political influence or involvement	0.750	12	0.839	4	0.788	7	0.784	10
Poor Supervision by Contractor	0.781	10	0.716	12	0.812	5	0.766	11
Lack of monitory and quality control	0.738	14	0.781	7	0.765	8	0.756	12
Inadequate Sanctions for Highway Facilities	0.762	11	0.774	8	0.682	13	0.752	13
Poor Supervision by client	0.742	13	0.671	16	0.788	7	0.728	14
No local Standard of Practice	0.712	17	0.761	9	0.706	11	0.726	15
Inferior asphalt mix design	0.712	17	0.716	14	0.741	9	0.718	16
Soil Type (Clay)	0.742	13	0.658	18	0.671	14	0.704	17
Prolonged flooding	0.704	18	0.677	15	0.741	9	0.702	18
Lack of efficient/competent contractor	0.723	15	0.652	19	0.671	14	0.692	19
No Laboratory and in situ test on existing subgrade	0.669	19	0.716	12	0.694	12	0.688	20
Large Traffic Volume	0.719	16	0.632	21	0.670	14	0.684	21
Lack of expert technical personnel by client, contractor, or consultant	0.665	20	0.658	18	0.659	15	0.662	22
No Local Professional Bodies in Highway Design, Construction and Maintenance	0.646	22	0.658	18	0.659	15	0.652	23
Oxidisation of bitumen over time	0.650	21	0.639	20	0.588	16	0.636	24
Slow administrative process by client	0.592	23	0.710	13	0.588	16	0.628	25
Delay on payments of contractor	0.554	25	0.677	17	0.553	17	0.592	26
Climatic Changes (Temperature)	0.573	24	0.568	22	0.553	17	0.568	27

1) Utility cuts by the Water and Sewerage Authority (W.A.S.A) (0.904),
2) Maintenance culture (0.898),
3) Quality of work (workmanship) (0.888),
4) Poor drainage facilities (0.862) and
5) Overloaded vehicles (0.854).

Conversely, the lowest-ranked factor was climatic changes (temperature), with a RII = 0.568.

Scholars such as, Adlinge and Gupta (2013) and Praveen and Ankit (2010) have arrived at similar findings concerning the most critical factors of road failure. They highlighted that sudden increase in traffic loading, temperature variation, poor construction, inadequate materials selection process and poor drainage were the most prevalent failure mechanisms, corresponding with three of the presented study's critical factors.

Figure 4 provides an overview and illustrates the ranking of state agencies contractors, consultants and combined, highlighting that these factors have the highest impact on the causes of frequent pavement failures of maintained roads in T&T. Although not top-ranked, Wilde (2002) indicated that utility cuts into the pavement introduce discontinuities and increase the roughness of the pavement structure, which has the potential to cause both structural and functional degradation of the pavement, which leads to premature pavement failure. Additionally, the correlation between poor maintenance culture and the cause of pavement failure, as similarly indicated in the present study and work by Okigbo (2012), highlight that those in authority do not release funds for road maintenance at the appropriate time, which consequently allow roads to deteriorate to the extent that they become impassable or more expensive to rehabilitate. It should be noted that the possible biases in responses vary because of the categories and duties of respondents (including state agency, contractor, consultant) of the study. This is evident in Figure 4 as it highlights that the contractors were the only agency that indicated political influence or involvement as causes affecting the maintenance processes of roadways.

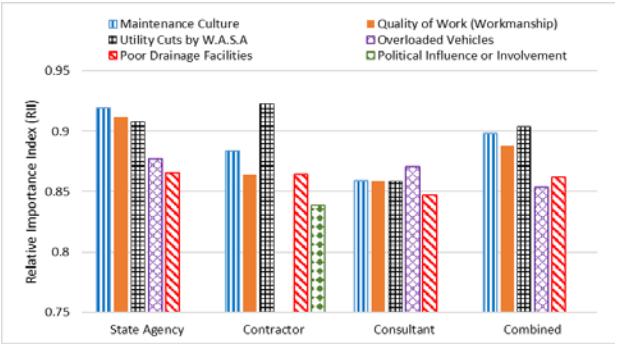

Figure 4. Major Causes of Frequent Failures of Maintained Roads in T&T

Moreover, the Water and Sewage Authority (WASA) utility cuts are the highest ranking contributing issue for road contractors, which they claim that it occurs after the construction stage of the road pavement structure. Their perspective is based on their responsibilities to provide a user-friendly, visually beautiful, and functional road product at the end of construction. The effort and quality with which they created the road is not the same as the devotion with which WASA patched the cuts, resulting in the early beginning of collapse.

The quality of workmanship is linked to the improper training of construction workers. The abovementioned results suggest that workmen in the local pavement construction industry may not be well trained. This view is supported by Okigbo (2012), who concluded that this lack of training amongst the artisans and craftsmen could lead to the inappropriate application of pavement construction materials or inadequate soil compaction. Another major cause of pavement failures is overloaded vehicles, which research (Abadin and Hayano, 2022; Pais et al., 2013; Sadegh and Fathali, 2007) has shown to cause fatigue cracking and rutting, eventually requiring pavement rehabilitation. The actions of overloaded vehicles will continue to wear down the pavement surface and, thus, gradually reduce the high-speed skid resistance. It is suggested that the increase in overloaded vehicles on a pavement that is already experiencing pavement deterioration would cost billions due to maintenance and rehabilitation and vehicle operating cost.

4.3 Impact of Effective and Timely Maintenance of Road in Trinidad

As indicated by the data in Table 2, poor maintenance of the roads in T&T inevitably causes unnecessarily traffic delays; however, this seldom discourages road users, thus not assisting with the appeasing heavy traffic. As in the case of Yitages (2017), this study highlights that the lack and mismanagement of maintenance increase the cost of rehabilitation and repairs, which progressively leads to pavement failures. Extensive rehabilitation and even re-construction could save TT$ millions if timely maintenance was carried out earlier. The data indicates that the advantages of timely and adequate road maintenance sustain the quality of the road infrastructure while simultaneously providing a level of safety to the road users.

The respondents were of the view that the quality achieved on maintained paved roads is not sufficient. They also lamented that the maintenance culture in T&T is considered reactive as opposed to being proactive. The best approach is one that addresses maintenance as soon as failures are identified to prevent further deterioration.

Moreover, the lack of adequate budgetary allocations leads to delays in effective and routine maintenance works. This finding corroborates the conclusions of Donev and Hoffmann (2020), who suggested that the objective of maintenance and repair works is to minimise agency and user costs or to minimise risk/environmental impacts by selecting the most appropriate treatments subject to budget constraints. Furthermore, the work highlights the correlation between the lack of technical training for road maintenance personnel, leading to poor management policy and the consequences of developing poor road conditions.

4.4 Pavement Deterioration on Economic Growth

Robbins and Tran (2015) suggested that smooth roads cost transportation agencies less over the life of the pavement and result in decreased highway user operating costs, delayed costs, decreased fuel consumption and decreased maintenance costs. As highlighted in Table 3, in T&T, there is a strong belief that effective and efficient road maintenance strategies lower vehicle operating costs (VOC). The VOC is considered to impact economic growth since poorly maintained roads directly would exhibit costly repairs to motorists' vehicles over time. Given the current economic climate of the Caribbean, 41% of the respondents believe that providing adequate funding for road maintenance works can improve the country's economic health.

Table 2. Responses Regarding the Impacts of Timely Maintenance

Statement	Strongly Disagreed (1)	Disagreed (2)	Neutral (3)	Agreed (4)	Strongly Agreed (5)
	%	%	%	%	%
Poor maintenance can unnecessarily cause traffic delays.	0	0	2	59	39
Lack of maintenance increases the cost of rehabilitation and repair.	1	0	0	38	61
Poorly maintained roads seldom discourage users or curb the volume of traffic.	8	33	14	38	7
Timely and adequate road maintenance sustains the quality and safety of the road.	0	0	0	55	45
The lack of technical training for road maintenance personnel's results in poor road conditions.	2	9	16	57	16
Lack of maintenance provides low service levels to its users.	0	2	11	56	31
Maintenance works are only executed when major failure occurs.	1	3	7	47	42
Mismanagement of maintenance works lead to the progression of pavement failures.	1	1	8	59	31
Lack of government's budgetary allocations for long-term commitment leads to delays in effective maintenance	1	9	17	36	37
The lack of sophisticated equipment and resources are limitations to effective maintenance.	10	32	23	25	10
Roads are considered sustainable when it is maintained in a satisfactory condition over time.	1	3	10	57	29

Table 3. Responses Regarding the Impact of Pavement Deterioration on Economic Growth

Statement	Strongly Disagreed (1)	Disagreed (2)	Neutral (3)	Agreed (4)	Strongly Agreed (5)
	%	%	%	%	%
Effective road maintenance can be considered the life blood of the economy and serve as a catalyst that fuel economic growth	2	5	20	50	23
Poor road maintenance can be considered hindrance to foreign investments	0	7	25	53	15
Delayed maintenance has the potential to impose a heavy burden on the economy	0	4	9	52	35
Deterioration of pavements is a clear indication of the decline of economic growth of a country	0	26	26	37	11
As roads deteriorate, the costs of essential goods and services begin to increase	1	5	16	56	22
Effective and efficient road maintenance lowers vehicle operating cost to the users	0	0	1	43	56
There is a causal relationship between well maintained pavement infrastructure and economic growth	1	4	31	48	16
The boost in the economy can only be achieved when adequate funding is provided for road maintenance works	2	26	31	30	11

Another area is the lack of data to make viable assessments and develop interventions that are unique to the country when thinking of transportation-economic growth policies. The poor or ineffective existing pavement management system (PMS) has uncovered major deficiencies locally. One of which is that the public road agency lacks an effective monitoring system. This deficiency has made it difficult to execute an adequate data collection policy that can be used to generate the necessary feedback on the road networks. The step forward to mitigate these issues is implementing a framework suited for analysing the economic effects of pavement maintenance. Such a framework can allow relevant stakeholders to analyse and implement maintenance projects properly.

The evidence-based framework will eliminate the existing ad hoc approach, which is currently being used in most instances. Other benefits of such a framework will be:

1) Improved development of a comprehensive strategic plan for road maintenance,
2) A more rigorous approach to analysing the correlation between pavement maintenance strategies and economic defects or benefits,
3) Initiating the development and improvement of policies, local codes, and regulations related to pavement maintenance, and
4) Access to historical data can inform decisions based on lessons learnt from successful or unsuccessful initiatives.

5. Conclusions

The literature revealed that well-maintained roads reduce the impacts associated with motorist safety, improve users' benefits and foreign investments' attractiveness, and boost economic wealth. The adverse effect of poorly maintained rood also holds true. The study investigated the causes of frequent failure of maintained roads in T&T. The results from the study suggest that the major causes of frequent failure of maintained roads are due to maintenance culture, quality of work (workmanship), utility cuts, overloaded vehicles, and poor drainage facilities in the country.

The study's approach investigated the perspectives of three important stakeholders on the prevailing reasons of road failures. The study's findings clearly show that there are significant disparities in key stakeholders' perspectives on what constitutes road failure in T&T. For example, the state agency and consultants argue that political influence is a factor, while the contractor places a high value on it. The involvement of each stakeholder clearly influences and unavoidably influences the ranking of these failure producing elements.

The research also sought to determine the impacts of pavement deterioration on economic growth and timely maintenance of roads in T&T. The results suggest that pavement deterioration can significantly impact economic growth both directly and indirectly, given that a functioning road transportation infrastructure serves as a catalyst that fuels economic growth. Furthermore, it was revealed that sufficient funding for maintenance works must be made available in a timely manner since the lack of budgetary allocations leads to delays in effective maintenance, which, consequently, can increase the cost of rehabilitation and repair.

Based on existing literature, case studies, and the current study's findings, the following points are recommended to stakeholders to diagnose the causes of frequent failures of maintained roads in T&T. These are:

1) Regularly assess the performance of the road networks to take timely corrective actions regarding the road condition. Random and sporadic maintenance interventions should be changed to specific and results-oriented condition responsiveness. Proper investigations into the causes of pavement failure will help bring an existing pavement to its original condition before the pavement deteriorates further.
2) Invest in Road Maintenance Management System (RMMS) or Pavement Management System (PMS) with adequate training for staff to manage the nation's road network effectively. This system systematically allows for proper planning,

scheduling, and budgeting of maintenance works with little to no political involvement.

3) Dedicate a special unit that should be solely responsible for developing maintenance schedules and budgets for the nation's road network.
4) The utility companies and road agencies should work together to ensure that road damages are properly repaired to reduce the effect of further pavement deterioration. Consideration for the construction of utility corridors along the roadways for future projects can significantly reduce the deterioration of the pavement structure.
5) Provision for automatic weight control devices at strategic locations to monitor overloaded vehicles. This should include the involvement of police and traffic wardens who should regularly patrol not only highways but also secondary and tertiary roads. All heavy vehicles operating on the nation's roads without the necessary permit should be charged in accordance with the law.
6) Road agencies and contractors have to take responsibility for the quality of work and workmanship and the failures that occur post maintenance work that can reduce the causes of frequent failure of maintained roads in Trinidad. Quality assurance methodologies for the post maintenance period need to be developed in order to determine whether the desired target is achieved or not.
7) Evaluate and adopt innovative maintenance strategies and maintenance treatment selection techniques to develop effective maintenance programmes for the nation's roads.

Further work is required to establish whether the findings of this research are consistent with other small island developing states in the Caribbean. The new studies can evaluate the alternative funding options for maintenance works, as well as innovative and sustainable alternative strategies and treatment selection techniques to develop effective maintenance programmes.

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Investigation of Compressive Strength of Slag-based Geopolymer Concrete Incorporated with Palm Oil Fuel Ash

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Abstract: *The paper investigated the compressive strength of ground granulated blast furnace slag-based geopolymer concrete incorporated with palm oil fuel ash compared to portland limestone cement concrete. An appropriate geopolymer mix design was first determined. This mix entailed fine aggregates: coarse aggregates: cementitious material: liquid ratio of 2: 2.5: 1: 0.5, respectively, with 100% replacement of portland cement with ground granulated blast furnace slag (GGBS) incorporated with palm oil fuel ash (POFA). An alkaline solution was used in place of water containing sodium hydroxide and sodium silicate. Following this design, five geopolymer mixes were prepared, each of varying POFA-GGBS ratios of 0:100, 25:75, 50:50, 75:25, and 100:0, and a 14M alkaline solution was used. In addition, a control mix was determined, comprising 100% portland limestone cement (PLC) as the cementitious material and 100% water. Three cubic samples were casted for each geopolymer mix with the control mix, and then the geopolymer mixes were thermally cured for 24 hours. The compressive strength test was conducted on the test samples after ambient curing of 7 days and 28 days, and values for compressive strength (MPa) and failure load (KN) were recorded. Through comparative analysis, it was determined that the most efficient geopolymer mix was mix 2 of GGBS: POFA ratio of 75:25 with 14M alkaline solution. Mix 2 achieved the highest compressive strength of 65.41MPa, approximately 21.99% higher than the strength attained by portland cement concrete samples, measured to be 53.62MPa. Thus, geopolymer concrete can achieve greater strength than portland cement concrete.*

Keywords: *Alkaline solution, Geopolymer concrete, cementitious material, ground granulated blast furnace slag, compressive strength, palm oil fuel ash*

1. Introduction

The most common type of cement used globally is portland limestone cement (PLC). PLC has become a major environmental threat because of the large quantities of CO_2 released during its production. Consequently, the vast quantities of CO_2 released into the environment deplete the ozone layer (Kamaldeep and Chamberlin, 2019). However, researchers such as Mehta et al. (1982), Poon et al. (2006), Shannag and Shaia (2003), Toutanji and El-Korchi (1995), and Wang et al. (2008) have proved that certain waste materials can improve concrete and mortar's strength and durability. The waste materials include rice husk ash (RHA), silica fume, ground granulated blast furnace slag (GGBS), fly ash (FA), and metakaolin, among others.

Palm oil fuel is one of the significant contaminants of water, air, soil, and surrounding ecosystems. Therefore, the need to focus more on geopolymer concrete which is an alternative way to reuse palm oil fuel and palm oil fuel ash (Zarina et al., 2013). Prabu, Shalini, and Kumar (2014) defined geopolymer concrete (GPC) as a hardened cementitious paste made from alkaline solutions and geologically sourced materials. These source materials include palm oil fuel ash, palm kernel shell ash (PKSA), rice husk ash, ground granulated blast furnace slag, and fly ash.

The two main constituents of GPC are alkaline activators and source materials. These two constituents of GPC influence the properties of geopolymer binders (Nurruddin et al., 2016). Saafi et al. (2013) opined that GPC production has significant advantages over PLC production, with the primary benefit being the relatively low production cost with energy-efficient processes. Further, GPC resists acid attacks and exposure to high heat and has a low shrinkage speed.

Davidovits (2013) also stated that the reaction type between a source material containing aluminium (Al) and silicon (Si) and an alkaline liquid is polymerisation reaction, which produces a family of mineral binders called geopolymers. Contrasting to portland limestone cement concrete, calcium-silicate hydrates is not the primary binder in GPC. Instead, the primary binder is an

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alumino-silicate polymeric gel formed by tetrahedral-bonded silicon and aluminium with oxygen atoms shared in between. Several studies suggested that when a source material like GGBFS containing large amounts of soluble silicate is added to the geopolymeric gel, a new C-S-H gel is formed due to calcium dissolution occurring at low alkalinity. Thus, this gel is the primary binder phase with small calcium precipitate scattered inside, and the GPC's mechanical strength is improved by the coexistence of the two binder phases (Yip et al., 2005).

Several researchers have also studied the feasibility of partially replacing cement with POFA. For example, Tay (1990) partially replaced cement with shell and fibre palm oil ash in concrete. His results proved that it is possible to replace up to 10% of cement with shell and fibre ash to produce GPC. Subsequently, Tay and Show (1995) reported the feasibility of partially replacing cement with oil-palm bunch ash without adverse effects on the concrete's strength and durability. Chindaprasirt et al. (2008) also reported that the introduction of POFA improved the resistance of mortar to chloride penetration.

For geopolymer concrete, compressive strength depends on the curing conditions, the concentration of alkaline liquids, age, and the ratio of binder contents. Curing in portland limestone cement concrete is conventional, which entails curing in water and ambient curing. However, the curing for GPC is quite different as many studies such as Kumaravel (2014) and Singh et al. (2015) determined that higher temperature is a vital parameter in achieving optimum compressive strength of GPC, suggesting oven or thermal curing at 60 - 80°C.

Nurruddin et al. (2018) also proved by an investigation that oven curing is most efficient for curing geopolymer concrete. The curing principle is that water is produced during the polymerisation of GPC, which is vaporised during thermal curing. This water vaporisation hardens the concrete, minimises drying shrinkage, and greatly increases compressive strength. This resulted in concluding that thermal curing is the most suitable for GPC. It was also observed by Nurruddin et al. (2018) that the longer the period of curing, the more the increase in strength. However, for optimum compressive strength, the period of curing had to be at least 20 hours and curing periods longer than 24 hours had no significant increase in compressive strength.

Many researchers, such as Yewale et al. (2016), have found that the optimum strength of GPC occurs at a curing temperature of 60°C. Similarly, several other researchers have shown through their studies on concrete and mortar that POFA improves compressive strength and sulphate resistance when it partially replaces cement. (Jaturapitakkul et al., 2007; Weerachart et al., 2007; Rukzon and Chindaprasirt, 2009; Weerachart et al., 2009). Further, an increase in water demand to achieve preferred workability for concrete when POFA partially replaced PLC was reported by Chindaprasirt et al. (2007). In contrast, the strength of concrete improved when PLC was replaced with 20% POFA, while concrete strength reduced when POFA content exceeded 20%.

Bamaga et al. (2013) also conducted a study on concrete where about 40% ground POFA was used. The study results showed that the properties of the hardened concrete, such as elasticity modulus, creep, poisson's ratio, shrinkage, and strength are similar to reference samples with as much as 30% POFA. Lastly, several researchers have concluded from their respective research that POFA has the potential to be utilised in concrete production because of its pozzolanic characteristics (Bamaga et al., 2013).

The present study investigated the compressive strength of slag-based geopolymer concrete produced with varying proportions of GGBS and POFA in comparison to portland limestone cement concrete. This is to assess the sustainability of using geopolymer concrete utilising GGBS and POFA.

2. Materials and Methods

2.1 Materials

The materials used for this research are sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), portland limestone cement (PLC), fine and coarse aggregates, palm oil fuel ash (POFA), ground granulated blast furnace slag (GGBS), and water. The NaOH and Na_2SiO_3 were purchased from a chemical supplies company in Oyo State, Nigeria. Likewise, PLC — Dangote of cement grade 42.5R — was purchased from a local cement store within Oyo State, and GGBS was sourced through Engr. Oyakhire from a steel company in Port Harcourt, Nigeria. 19mm angular and well-graded coarse aggregate material were used, while natural river sand as fine aggregates. Further, both aggregates used were sourced locally within Oyo State, Nigeria. Finally, palm oil fuel was sourced locally from a palm oil mill within Ekiti State, Nigeria.

2.2 Materials Characterisation

2.2.1 Chemical Compositions

X-ray fluorescence (XRF) spectrometry analysis was conducted to determine the oxides compositions of the POFA, GGBS, and PLC materials used, with the results shown in Table 1.

Table 1. Oxides Composition of POFA, GGBS and PLC

Oxides	POFA (%)	GGBS (%)	PLC (%)	POFA (%)
SiO_2	64.47	35.77	21.60	64.47
Al_2O_3	2.63	14.11	5.85	2.63
Fe_2O_3	5.23	0.92	2.78	5.23
CaO	4.70	36.52	64.30	4.70
MgO	3.67	9.45	1.42	3.67
Na_2O	0.18	0.30	0.14	0.18
K_2O	7.55	0.52	0.72	7.55
SO_3	0.82	1.08	2.03	0.82
LOI	15.8	1.45	1.38	15.8

According to BS EN 450-1 (BSI, 2012) and BS EN 8615-2 (BSI, 2019), a suitable material as a pozzolanic binder must have the addition of its SiO_2, Al_2O_3 and Fe_2O_3 constituents equal at least 70% of its % composition. The POFA material satisfied this chemical pozzolanic requirement, as the sum of its SiO_2, Al_2O_3 and Fe_2O_3 equals 72.33%. Thus, it can be used as a binder in GPC production. Further, the chemical composition of the POFA material used is similar to that obtained from a study by Ranjbar et al. (2014).

Likewise, the GGBS used satisfied the requirements of BS EN 15167-1 (BSI, 2006), which states a range of 32 - 40% for SiO_2 (35.77%) and CaO (36.52%) contents in GGBS. In addition, the composition of the GGBS material is similar to that obtained in a previous study by Oyebisi et al. (2022). Thus, it can be deduced that the GPC material exhibited cementitious reactivity and is suitable for GPC production. Similarly, the PLC used satisfied the chemical requirements stated in BS EN 196-2 (BSI, 2016).

2.2.2 Microstructural behaviours

Figures 1 (a), (b), and (c) show the Scanning Electron Microscopy (SEM) images of POFA, GGBS, and PLC. From the SEM images, it can be deduced that POFA has a large and irregular shape with a porous structure, while PLC has an angular shape with its internal structure wrinkled to a limited extent. Further, GGBFS has an amorphous shape with uneven surfaces. Thus, the structure and shape of the particles of POFA and GGBS significantly contribute to the geopolymer concrete's properties, as Thomas (2007) established.

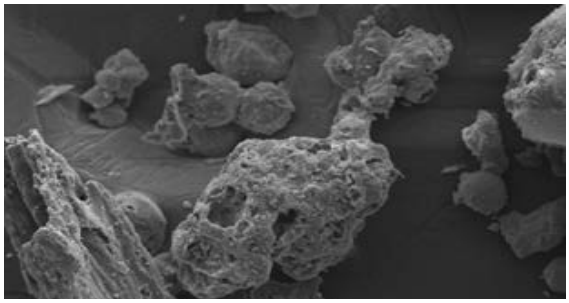

Figure 1(a). SEM of POFA (Tonduba and Mirza, 2017)

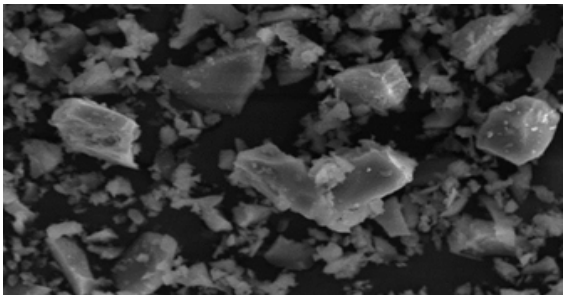

Figure 1(b). SEM of GGBS (Adam et al., 2009)

Figure 1(c). SEM of PLC (Oyebisi et al., 2022)

2.3 Preparation of POFA

The sourced palm oil fuel was burnt and calcinated in a foundry workshop. Firstly, the palm oil fuel was burnt in the open air to ashes, and after that, a 300μm sieve sieved the ashes to remove undesired particles. Next, batches of the POFA material were calcinated in a closed furnace under a maximum temperature of 500°C for approximately 7 - 8 hours. Finally, the palm oil fuel ash was left to cool. After cooling, a miller ground the ash to obtain it in its finest form, having a maximum particle size of 45μm, as shown in Figure 2.

Figure 2. Calcinated Palm Oil Fuel Ash

2.4 Preparation of Alkaline Solution

The alkaline solution was prepared 24 hours in advance under standard laboratory conditions, as suggested by Kumar (2015). A 14 molar concentration of the alkaline activator with a ratio of 1: 2.5, as recommended by Venkatesan and Pazhani (2016), was formed from the reaction of sodium silicate (Na_2SiO_3) with liquid sodium hydroxide (NaOH).

2.5 Geopolymerisation Reaction and Mechanism

Geopolymerisation is a complex process that involves a rapid chemical reaction between a source material containing aluminosilicate and an alkaline solution. This chemical reaction produces a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Abdullah et al., 2011). Further, the composition of the product of a typical geopolymerisation process is expressed as $nM_2O \cdot Al_2O_3 \cdot xSiO_2 \cdot yH_2O$, where “M” is an alkaline element and “n” is the degree of polycondensation (Davidovits, 1994).

In addition, Davidovits (2008) stated that Si to Al ratio significantly influences a geopolymer's ultimate structure. Thus, geopolymer materials with a Si to Al ratio of 2 to 3.5 have very rigid structures and are suitable for constructing infrastructure projects. Davidovits (2008) also stated that polysialates (-Si-O-Al-O-), polysiloxo sialates (-Si-O-Al-O-Si-O-), and poly-disiloxo sialates (-Si-O-Al-O-Si-O-Si-O) are the three types of polysialates present in geopolymers. The chemical structures of the three polysialates are shown in Figure 3.

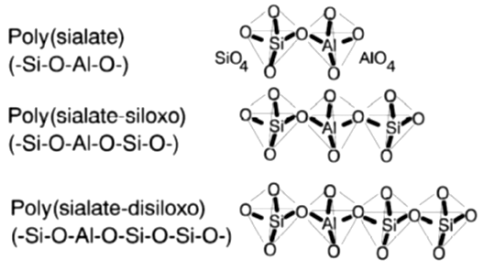

Figure 3. Chemical Structures of Polysialates
Source: Abstracted from Abdul Aleem et al. (2013)

Aziz et al. (2016) opined that the formation mechanism of the setting and hardening of a geopolymer material involves a chemical reaction with the three steps listed below and depicted by Eq. 1-3, as shown in Figure 4.

1) Dissolution of Si and Al atoms in the alkaline solution.
2) Reorganisation and diffusion of dissolved ions into monomers.
3) Polymerisation of monomers into polymeric or hydrated products.

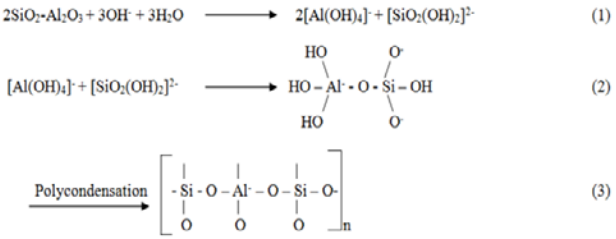

Figure 4. Three Steps of a Geopolymerisation Process
Source: Abstracted from Aziz et al. (2016)

During the formation of geopolymer concrete, water is usually released while curing the concrete. However, water is usually absorbed due to hydration during the curing process of PLC concrete. Thus, the difference in the curing processes due to the heat applied to facilitate polymerisation in geopolymer concrete significantly influences its mechanical and chemical properties and resistance to chemical attacks, water ingress, alkali–aggregate reactivity, and heat (Abdul Aleem et al., 2013).

2.6 Life Cycle Analysis (LCA) of Materials

GPC is an efficient alternative to PLC concrete because of its excellent durability properties and resistance against sulphate and acid attacks, higher mechanical strength, and lower heat of hydration (Hardjito and Rangan, 2005). Other beneficial outcomes of GPC production include environmental preservation, conservation of natural resources, and reduced disposal of waste materials into landfills (Venkatesan and Pazhani, 2016). While vast amounts of waste from agricultural and industrial processes such as POFA and GGBS are generated globally and usually disposed of in landfills, these wastes can be utilised in GPC production as cementitious materials (Malkawi et al., 2018; Mannan and Ganapathy, 2004).

In addition, for every 1Kg of PLC produced, 1Kg of CO_2 is emitted into the surroundings (Hardjito and Rangan 2005). Davidovits (2013) further broke this one-to-one ratio by explaining that 1 tonne of PLC generates 0.55 tonnes of CO_2 and an additional 0.40 tonnes when combusting carbon fuel. Therefore, sustainable alternatives to PLC concrete production are essential to reduce potential health hazards and environmental pollution problems.

2.6.1 LCA of POFA

The palm oil industry is one of the world's most essential industries; the by-products of a palm oil plantation are shown in Figure 5. According to UNDP (2007), the world is estimated to produce more than 295 million tonnes of waste annually, with about 90% produced in Malaysia and Indonesia and both countries accounting for 90% of global production and trade in palm oil. Thus, it becomes crucial to make sustainable use of the vast amounts of waste generated from palm oil plantations and related industries (Ofuyatan et al., 2021).

Figure 5. By-products of a Palm Oil Plantation

POFA is a solid waste produced from power plants in palm oil mills. It is usually obtained by burning empty

fruit bunches and shell and palm oil fibres as fuel in boilers. Further, palm oil mill operators often dump POFA around the mill area or in open areas without control (Bamaga et al., 2013). As a result, the increasing amount of POFA has become a contamination source to surrounding ecosystems, and therefore needs attention to prevent further harm to the environment (Zarina et al., 2013).

Additionally, several researchers have investigated the feasibility of using POFA as a partial cement replacement to produce high-performance concretes and reduce the environmental challenges caused by POFA (Thomas et al., 2017). Finally, the findings support the potential utilisation of ground POFA as supplementary cementing material in normal and high-strength concrete production due to its significant pozzolanic characteristics (Bamaga et al., 2013).

2.6.2 LCA of GGBS

Over 400 million tons of slag are produced each year globally (Kumar et al., 2019). Thus, several researchers have also studied slag due to the possibility of recycling steel production residues to produce new resource-efficient and low-carbon pozzolanic binders for concrete production (Di Maria et al., 2018). Slag is a very popular by-product of iron and steel production, commonly used as a cementitious material today. It is formed by running molten slag produced in a blast furnace directly into a pit of water or steam, or a combination of both. This quenches the molten slag, producing a glassy granular substance, which can then be ground into a fine powder to form GGBS (Prabu, Shalini and Kumar, 2014).

According to a study by Di Maria et al. (2018), it was proved that the binder properties of GPC can be activated by carbonation and alkali activation processes. Further, the study stated that utilising GGBS through alkali activation and carbonation to produce new cementitious construction materials would help reduce the environmental challenges and threats posed by cement and concrete industries. It has also been proved by Maghool et al. (2017) that GGBS poses no environmental threat for use in construction, and its use will result in a feasible and sustainable alternative for reuse of the vast amounts of slag in landfills.

Concerning CO_2 emissions, there is a considerable reduction of 80% of CO_2 emissions compared to that of PLC (Davidovits, 2013). The study also indicated that the energy needed for every 1 tonne of PLC requires approximately 4700 MJ of electric power. In comparison, there is a significant reduction of 59% in the energy requirements for GGBS as a by-product of steel. Consequently, using GGBS will considerably decrease the comprehensive environmental issues of PLC production and improve the benefits of land resources and energy and materials conservation. However, global warming and acidification potential remain slag production's most significant environmental impacts (Li et al., 2016).

2.7 Mix Design of Test Samples

Various trial mixes were performed until the control mix of PLC resulted in 50MPa, as shown in Table 2. Five (5) mixes were considered whereby GGBS was replaced with POFA by 0, 25, 50, 75, and 100%, denoted as Mix 1, Mix 2, Mix 3, Mix 4, and Mix 5, respectively. Table 3 shows the varying quantities of GGBS and POFA in each mix.

Table 2. Mix Design of Grade 50 Geopolymer Concrete

Raw material	Ratio	Quantity per 100 mm cube
Coarse aggregates	2.5	1.0 kg
Fine aggregates	2.0	0.8 kg
Cement (PLC) / Cementitious materials (GGBS and POFA)	1.0	0.4 kg
Liquid (Water/Alkaline solution)	0.5	200 ml

2.8 Mixing and Casting of Samples

Before mixing and casting, moulds were cleaned with a clean, moist cloth to remove dust. After that, the moulds were lubricated with oil. The sandwich mixing method was adopted to minimise errors and encourage a more homogenous mix. Further, the required volume of the prepared alkaline solution was measured using a measuring cylinder and mixed with the solid components to form a homogenous mix. Immediately after mixing the freshly prepared concrete, it was filled into the moulds and vibrated. The vibration was crucial to ensure the concrete was properly compacted and reduce air voids. In addition, the resulting cubes were left to set for 24 hours to allow for adequate polymerisation and enhancement of mechanical properties. The cast test samples are shown in Figure 6.

2.9 Curing and Testing of Samples

The cubes were demoulded after 24 hours of proper polymerisation and enhancement of mechanical properties. After that, the test samples were thermally cured in an oven for 24 hours at a temperature of 60±3°C.

Table 3. Composition of Mixes 1-5 per 100mm Cube

Mix	Coarse Aggregates (kg)	Fine Aggregates (kg)	GGBS (%)	GGBS (kg)	POFA (%)	POFA (kg)	NaOH Solution (ml)	Na_2SiO_3 Solution (ml)
1	1	0.8	100	0.4	0	0	57	143
2	1	0.8	75	0.3	25	0.08	57	143
3	1	0.8	50	0.2	50	0.16	57	143
4	1	0.8	25	0.1	75	0.24	57	143
5	1	0.8	0	0	100	0.32	57	143

Figure 6. Test Samples

Afterward, the test samples were cooled to room temperature to avoid a sudden temperature change. They were later laid out in an area within the laboratory untouched for two test periods of 7 and 28 days at room temperature (approximately 30°C).

At the end of the 7 and 28 days of curing the test samples, a density test was conducted. Afterward, the compressive strength of the test samples was performed using BS 1881-116 (BSI, 1983). Therefore, the PLC and GPC samples were crushed using a compressive strength-testing machine. The machine applied loads on the samples, as shown in Figures 7(a) and (b), and the compressive strengths were recorded. From the latter, the failure load values were calculated and recorded.

(a) (b)

Figure 7. Compressive Strength Test on Samples

3. Results and Discussion

3.1 Density Test

The average densities of the test samples after 7 and 28 days of curing are presented in Table 4. Figure 8 shows that the average density of the GPC mixes decreased with increasing POFA content. When compared with the control PLC mix, the decrease in average density at 7 days is 1.15%, 2.13%, 4.01%, and 9.54% for Mix 1, Mix 2, Mix 3, and Mix 4, respectively, while it is 0.87%, 1.30%, 3.17% and 6.51% at 28 days for Mix 1, Mix 2, Mix 3 and Mix 4 respectively. By comparing only the average densities of the GPC mixes, the results above show why Mix 1 and Mix 2 have better compressive strengths than Mix 3 and Mix 4. This is because density highly influences the mechanical properties of concrete, and denser concrete can more easily achieve fewer voids, low water absorption, low permeability to soluble substances and water, higher strength, and better durability.

Table 4. 7 and 28 Days Average Densities of Test Samples

Mix	Average density (kgm^{-3}) at 7 days	Average density (kgm^{-3}) at 28 days
PLC	2347	2303
GPC Mix 1	2320	2283
GPC Mix 2	2297	2273
GPC Mix 3	2253	2230
GPC Mix 4	2123	2117
GPC Mix 5	-	-

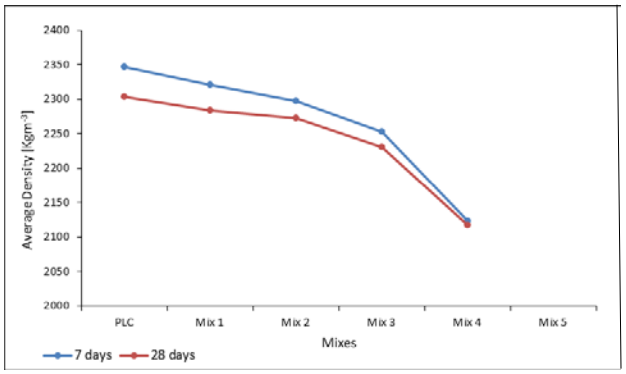

Figure 8. Average Densities of GPC and PLC Mixes at 7 and 28 Days

3.2 Compressive Strength Test

The average compressive strengths of the test samples after 7 and 28 days of curing are presented in Table 5. Figures 9 and 10 show that average compressive strength increases for the first two mixes with 100% GGBS – 0% POFA and 75% GGBS – 25% POFA respectively, while it decreased for the last two mixes with 50% GGFBS – 50% POFA and 25% GGBS – 75% POFA respectively. In addition, the average compressive strength of Mix 1 and Mix 2 at 28 days are 8.28% and 21.99% greater than that of the control mix of PLC, respectively, while that of Mix 3 and Mix 4 are 59.12% and 81.15% lower than that of the control mix of PLC respectively. For Mix 5, specimens did not set nor harden as they collapsed upon demoulding. The results above imply that Mix 1 and Mix 2 can withstand and resist more compressive loading without any crack or deflection than the control mix of PLC, hence, suitable for commercial and industrial structures

and in cases where high thermal and chemical resistance are required. On the other hand, Mix 3 and Mix 4 are suitable for domestic use.

Table 5. 7 and 28 Days Average Compressive Strength of Test Samples

Mix	Average compressive strength (MPa) at 7 days	Average compressive strength (MPa) at 28 days
PLC	32.79	53.62
GPC Mix 1	34.83	58.06
GPC Mix 2	42.11	65.41
GPC Mix 3	15.23	21.92
GPC Mix 4	6.46	10.11
GPC Mix 5	-	-

3.3 Optimum Percentage Substitution of GGBS and POFA

Figures 8, 9, and 10 show that the mix with the optimum percentage substitution of GGBS and POFA is Mix 2, which corresponds to 75% GGBS – 25% POFA and has its average density and compressive strength at 28 days to be 2273Kgm^{-3} and 65.41MPa, respectively. Therefore, the optimum percentage substitution of GGBS and POFA recommended is 75% GGBS – 25% POFA.

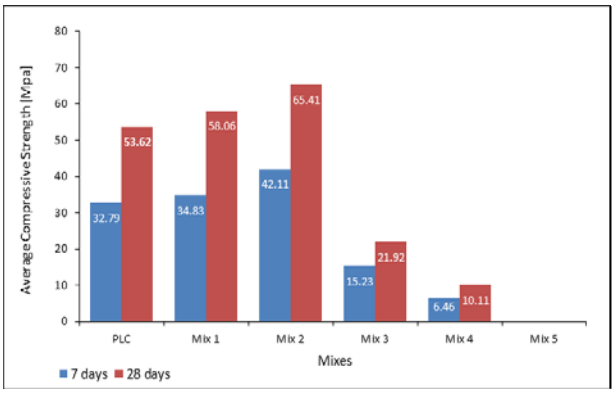

Figure 9. Average Compressive Strength of GPC and PLC Mixes at 7 and 28 Days

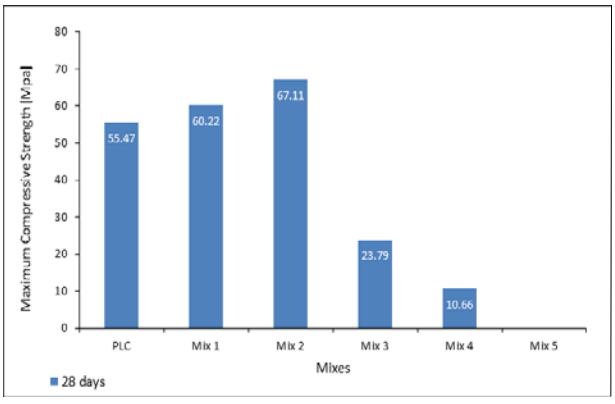

Figure 10. Maximum Compressive Strength of GPC and PLC Mixes at 28 Days

4. Conclusions

Geopolymer concrete is highly efficient in reducing portland limestone cement production and, thus, carbon footprints in the construction industry. The following can be deduced from the findings of this study:

1) GPC Mix 1 and GPC Mix 2 obtained the highest compressive strengths, which were 8.28% and 21.99% higher than the control PLC mix after 7 and 28 days, respectively.
2) GPC Mix 2 (75% GGBS – 25% POFA) achieved the highest compressive strength of 65.41MPa because of the reasonably high fineness of POFA particles, high packing factor, and increased pozzolanic reactivity in the geopolymer process.
3) The GPC Mix 5 containing 0% GGBS – 100% POFA cannot be considered an alternative to conventional concrete because the test specimens did not harden. The specimens did not harden because of the absence of GGBS to contribute more SiO_2 and Al_2O_3 contents and aid calcium dissolution to enhance the compressive strength of the mix.
4) The GPC mixes blended with POFA demonstrated low workability because of the increased alkaline solution demand due to the porous structure and large surface area of the ground POFA particles.

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The Department of Civil Engineering, UWI St. Augustine: A Historical Note of 1972-2001

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Abstract: *This paper is a continuation of a history of the Department of Civil Engineering at The University of the West Indies (UWI) at St. Augustine. It thus extends an account of its formative decade 1961-1971 previously published (in 2013) in The West Indian Journal of Engineering. The three subsequent decades covered herein encompass milestones, and transformations: (a) beginning of graduate level research, (b) commencement of an MSc programme in Construction Engineering and Management, (c) change of name from Civil to 'Civil and Environmental' for embracing the heightened awareness of environmental concerns, (d) relocation into a purpose-built building with a floor space of approximately 5,000 m^2, (e) construction of new environmental engineering, engineering geology, highway engineering, soil mechanics and structural engineering laboratories, (f) expansion and modernisation of the fluid mechanics laboratory, and (g) introduction of the semester system with its credit-based curriculum and assessment. Besides, there was a fivefold increase in student enrolment, followed by a sharp decline, and an increase in academic staff strength from six to twenty. This period also witnessed a gradual loss of regional diversity of its undergraduate students from a high of approximately 50 % in 1972 to less than 10% in 2001. On the other hand, there was a notable, and opposite, change in gender (female/male) ratio among the students – from less than 10%/90% in 1972 to approximately 50%/50% in 2001. Finally, the accreditation of the department's degree programmes by the Engineering Council in the United Kingdom (UK), as well as the triennial visit of overseas external examiners, inherited from its inception, were maintained.*

Keywords: *Civil Engineering; Coastal Engineering; Environmental Engineering; Education; History; University; West Indies*

1. Introduction

In October 1973, a distant world event became the catalyst for change for the Department of Civil Engineering, hereafter referred to as the department, and equally for the Faculty of Engineering at The University of the West Indies (UWI) at St. Augustine, and Trinidad and Tobago (T&T). Specifically, it was the Arab Israeli war which greatly increased the price of petroleum. The ensuing windfall provided an opportunity, inter alia, to build/ expand/modernise the country's infrastructure – airports, hospitals, industrial estates, ports, public buildings, roads, and water supply. Some of the prominent public buildings thus built in Trinidad are the Hall of Justice, the Central Bank Towers and the Mount Hope Medical Complex. Moreover, the Priority Bus Route, the Uriah Butler Highway, the Point Lisas Industrial Estate, and the O'Meara Industrial Estate in Trinidad, and the Claude Noel Highway in Tobago were built from the increased petroleum wealth. Further, the newfound wealth gave an impetus to build the Arena and the Lower Navet dams, previously envisaged for increasing the capacity of public water supply in Trinidad. Therefore, there was an urgent need to train more civil engineers, both at the undergraduate and postgraduate levels. The objective of this paper is to chronicle how a hitherto small department, then only a decade old (Ellis and Shrivastava, 2013), addressed this need.

Photograph 1. I D C Imbert Building (*Completed 1986*)
Photo Credit: Author
Civil and Environmental Engineering, UWI St. Augustine

2. Heads of Department

During the three decades spanning this paper, there were six heads of departments. Information about the first, Professor Ponnambalam Selvanayagam, who served for six years 1968-1974 is sparse. An earlier publication (Ellis and Shrivastava, 2013) essentially provides all that is known about his links with the department. Further, out of

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the remaining five (see Photograph 2), comprehensive profiles, as Caribbean icons, are provided for the three (Harry Orville Phelps, Myron Wing-Sang Chin and I D C Imbert) by the National Institute of Higher Education Research Science and Technology of Trinidad and Tobago (https://icons.niherst.gov.tt/profiles/). Besides, there are memorial articles (Bretton, 2012; Shrivastava, 2017; Shrivastava and Imbert, 2018) for Professor Ignatius Desmond C. Imbert, Mr. Raymond Charles and Professor Harry Phelps, respectively. Accordingly, this paper provides only those aspects of the five heads of department which specifically relate to the periods of their respective headships.

Harry Orville Phelps 1974-1986 | Anil Kumar Sharma 1986-89; 1995-98 | Myron Chin 1989-1992

I D C Imbert 1992-95 | Raymond Charles 1998-2001

Photograph 2: Five Heads of Department (1974 – 2001)
Photo Credits: Department of Civil & Environmental Engineering

The Late Professor Harry Phelps (1926-2018) established the ethos of the department. Among these was an insistence that academic staff should normally be present in their office during working hours for students' consultation. He also ensured strict adherence to examination protocols – preparation of error free and lucid examination question papers within the stipulated deadlines, and rigorous and timely marking of examination scripts.

Professor Anil Sharma focused on academic staff recruitment. Professor C. Venkobachar and Dr. K. Venkatraman were recruited from India for filling vacancies in Environmental and Geotechnical Engineering respectively; Mr. Keith Sirju and Dr. Richard Clarke were recruited locally for filling vacancies in structural engineering. Notably, Professor Sharma served as the editor of the West Indian Journal of Engineering.

Dr. Myron Chin connected the department to the society through mounting continuing education courses for engineers, and for the National Emergency Management Agency (NEMA). Among his contributions the following two are prominent: (a) seismic risk evaluation of critical infrastructure in Trinidad, and recommendations for retrofitting the same; (b) development of a Caribbean Uniform Building Code (CUBiC).

The Late Professor Desmond Imbert (1931-2010) was passionate about keeping the curriculum linked to the foundational aspects of the subjects taught. Hence, he advised that the syllabi be as brief as possible to avoid distortion with time. He concurrently led the MSc programme in Construction Engineering and Management. He preferred to meet staff in the openness of corridors and walkways, and always reminded academic staff to publish only in high quality scholarly journals and not to become a pamphleteer.

The Late Mr. Raymond Charles (1951-2017) pioneered regional Coastal Engineering Training Courses in different Caribbean Islands and was instrumental in starting an MSc in Coastal Engineering. His initiative for the department to take the lead in Coastal Engineering was rooted in his observation that major roads in the Commonwealth Caribbean islands, owning to their generally mountainous landscapes, were built along the coastline. These are vulnerable to coastal erosion, especially during the passage of hurricanes.

3. Expansion, Rebranding, and Restructuring

With an increase in student numbers (see Figure 1), two needs emerged: (i) additional floor space, and (ii) additional teaching and support staff. In response to the first need, temporary wooden buildings were constructed in 1976 – with classrooms, offices, and a large drawing room. Alongside, the budgeted academic staff strength was increased from six to twenty (see Table 1). In 1986, the temporary wooden buildings were replaced with a purpose-built building (see Photograph 1), later renamed after the late Professor I D C Imbert. While the student numbers varied in response to the fluctuations in T&T's petroleum-based economy, the academic staff strength remained constant. This motivated an increase in research activities in mounting continuing education courses and for developing the previously mentioned postgraduate course in Coastal Engineering in 2001.

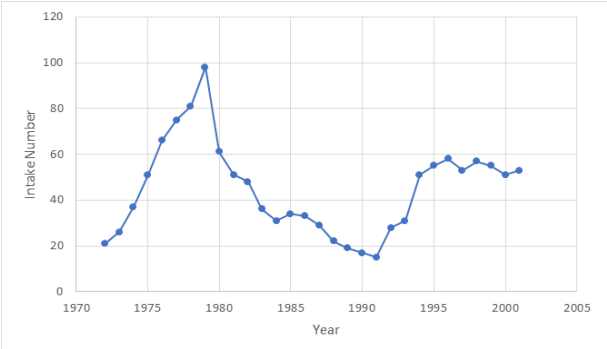

Figure 1. Student Intake Numbers 1972-2001
BSc Civil Engineering and Civil with Environmental Engineering
Source: Department's Submission Document for UK Engineering Council Accreditation 2001

Table 1. Academic Staff (Nationality other than T&T)

1972	**2001**	*Remarks*
P. Selvanayagam (Sri Lanka) Compton Deane Ignatius Desmond Imbert Harry Orville Phelps Leon Taylor (Grenada) Gerald Webb	Raymond Charles Myron Chin Vincent Cooper Derek Gay Madaniyo Mutabazi (Tanzania) Ian Khan-Kernahan Richard Clarke Abraham Mwasha (Tanzania) Robin Osborne (Dominica) Everson Peters (Grenada) Timothy Michael Lewis (UK) Kangala Ramamurthy (India) Cassandra Rogers Anil Kumar Sharma (India) Gyan Shrivastava (India) Keith Sirju Winston Suite K. Venkataramana (India) Chintanapalli Venkobachar (India) Rupert Williams	The following were members of academic staff in the intervening period: Gregory Andrews David Gunaratnam (Sri Lanka) Colm Imbert William Milne-Home Emru Millette Samuel Naranjit Joseph Srilal Perera (Sri Lanka) Winston Rajpaulsingh Kandula Sarma (India) David Smith (Jamaica) Percival Thomas (Sri Lanka) Ronald Williams

The four floors of the I D C Imbert building provided approximately 5,000 m^2 floor space for staff offices, new laboratories for Structural Engineering, Highway Engineering, Geotechnical Engineering and Engineering Geology. Additionally, three design studios, four lecture rooms, and two tutorial/seminar rooms were created. On the other hand, an architectural design flaw in the new building created frequent, and often prolonged, inconvenience to its occupants. Put another way, extensive use of glass in staff offices created a greenhouse effect during the breakdown of its water chilled central air-conditioning system. In hindsight, its architectural design should have provided pathways for the north-east trade winds, for alleviation of heat during breakdowns of its air-conditioning system.

The old structural engineering laboratory, located diagonally opposite to the Faculty of Engineering workshop, was converted into a new Environmental Engineering Laboratory in 1985. At the same time, the Fluid Mechanics Laboratory was expanded and renovated. It was then equipped with a number of new apparatuses: a hydraulic bench with pumps in series and parallel, dynamics of vortices apparatus, pipe friction apparatus, pressure transient apparatus, a sediment transport flume, a Hele Shaw apparatus and a subsonic wind tunnel for Wind Engineering (see Photograph 3).

The 1990s brought an awakening: it became obvious that though civil engineers have a leading role in the matters relating to the environment, as builders of infrastructure, they risked being marginalized by other disciplines in an era of growing public interest in sustainability and environmental preservation. No doubt, civil engineering departments elsewhere had foreseen such a trend and had changed their names from civil to civil and environmental, for example – Imperial College, Massachusetts Institute of Technology and Stanford University, to name a few. In 2000, after a considerable debate the department changed its name from Civil Engineering to 'Civil and Environmental Engineering'. Consequently, two undergraduate degree programmes were simultaneously offered: civil engineering, and civil with environmental engineering.

Photograph 3. Sub-sonic Wind Tunnel, Fluid Mechanics Laboratory (May 1996)
[L to R – Anil Sharma (Head of Department), Guru Kochhar (Dean, Faculty of Engineering), Samuel Hinds (Prime Minister, Cooperative Republic of Guyana), and the author)]
(Photo Credit: C. Kanhai))

A milestone, starting in 1990, was the switch from its UK based academic year comprising three terms to a two-semester system. Such a move was a UWI-wide decision which the department was obliged to follow. The stated objectives were said to extend the teaching period and conformity with universities globally, particularly in

North America. Nonetheless, it required a restructuring of the overall curriculum and individual courses, and timetables for lectures, tutorials, and laboratory and field sessions. Additionally, a system of course credits and grade points were brought into the teaching and examination rubrics. This transition took five years (1990-1994), during which two parallel systems of course delivery and examinations were implemented.

4. Introducing MSc Construction Engineering and Management

An MSc programme in Construction Engineering and Management (CE&M) commenced in 1978 for meeting the gathering pace of construction in the wake of the petroleum windfall previously mentioned. Its objective was to train civil engineers for managing large construction projects and equip them with skills in areas of optimal sequencing of myriad activities at construction sites, risk management, cost control and human resource management.

This programme was designed and delivered under the leadership of the late Professor I D C Imbert. For this purpose, three academic staff – Mr. T. M. Lewis, Mr. R. Osborne, and Mr. S. Perera - were initially recruited. Four years later, Dr. K.N. Ramamurthy and Dr. W. H. E. Suite joined the CE&M teaching staff. Upon the retirement of Professor I.D.C. Imbert in 1996, Professor Winston Suite took over the leadership of this programme. Since its inception, approximately two hundred students completed this MSc programme. Its part-time mode was favoured by those in full-time employment, and consequently many completed the programme in two or three years. Often, completion of MSc project reports was the main delaying factor. Nonetheless, with its mix of engineering and management, this programme was well received by the construction industry.

5. Research Activities in the Department

The Department, to its credit, created a strong tradition of research in its formative years (Ellis and Shrivastava, 2013). Thereafter, the early seventies saw the culmination of a regional research project on coastal erosion in the Eastern Caribbean (Deane et al., 1973), and the beginning of experimental research in hydraulic engineering (Phelps et al., 2021A and 2021B). To these, twelve PhDs (see Table 2) added to the body of the department's research. Additionally, eight published works give a flavour of research activities in the department. These are:

1) Resource Sharing in Linear Construction (Perera, 1983),
2) UWI Experimental Catchment Research Project, 1986 (see *Annex A*),
3) Hurricane Resistant Housing Design (Osborne et al., 1992),
4) Soil Mechanics of Trinidad's Expansive Clays (Ramana and Phelps, 1993),
5) Properties of Bitumen from Lake Asphalt (Charles and Grimaldi, 1996),
6) Torsion of thick-walled open concrete sections (Khan-Kernahan, 1997),
7) Impact of Sea Level Rise on Coastal Aquifers (Shrivastava, 1998), and
8) Aerodynamics of a Cricket Ball (DaSilva and Shrivastava, 2001).

6. Impact of Computers, Declining Regional Diversity and Changing Gender Ratio

The use of desktop computers first commenced in the mid-1980s, followed by laptops in the mid-1990s. The exponential increase in the use of computers by staff and students alike has had positive as well as negative impacts in teaching and learning. The positive impacts were self-evident, but the negative impacts were generally overlooked.

Table 2. PhDs Awarded (Nationality other than T&T)

Name	Title (Supervisor)	Year
Gyan Shrivastava (India)	The optimisation of pumping operations in the El Socorro aquifer (Harry Phelps)	1978 (May)
Winston Suite	A study of Melajo and Gunapo aggregates and the properties and behaviour in the fresh and hardened states of concrete made with these aggregates (I D C Imbert)	1978 (July)
Carson Charles	Linear systems approach to transportation modelling in Northern Trinidad (John Underwood)	1981
Joseph Perera (Sri Lanka)	Linear programming models in construction planning and control (I D C Imbert)	1983
Anthony Joseph	Structural utilisation of local timbers (A K Sharma)	1984
Timothy Lewis (UK)	An investigation into technology and technological change and their special relationships with engineering and development (I D C Imbert)	1989
Robin Osborne (Dominica)	Factors affecting selected methods of testing concrete for compressive strength (I D C Imbert)	1990
Firdaus Kamalodeen	Strength and behaviour of fibre reinforced concrete beams under combined bending, shear, and torsion (Anil Sharma)	1993
Ian Khan-Kernahan	Structural behaviour of bridge decks (Anil Sharma)	1994
Reynold Stone	Microcomputer-based model for surface runoff prediction from small agricultural watersheds in Trinidad (Harry Phelps)	1995
Richard Clarke	The hysteretic behaviour of ferrocement-retrofitted clay block masonry walls under in-plane reversed cyclic lateral loads (Anil Sharma)	1997

Source: The Alma Jordan Library, UWI St. Augustine

Among the negative impacts were a lessened ability to solve a problem from first principles and prepare sketches by hand. Further, it made plagiarism in coursework more difficult to detect, due to the use of identical software. In later years, the Internet has exacerbated this aspect in all study fields including engineering (Park, 2003). Furthermore, computers and slide projectors gradually replaced the blackboard/whiteboard in the classrooms. This reduced beneficial human interactions because a chalkboard/whiteboard is natural to the teaching of science and engineering – where intricate diagrams and equations need to be drawn and derived. Moreover, it is simple, reliable, spontaneous, and due to its slower pace permits the students to take notes. In sum, eyes, ears, and hands operate at the same time, and this improves concentration and learning. Its virtual disappearance is a loss in a high-tech world (Ressler, 2004).

The three decades covering this paper also saw a gradual decrease in regional diversity amongst its undergraduate students. In the author's observation, the number of students coming from outside Trinidad and Tobago decreased from approximately 50 % in 1972 to less than 10% in 2001. Recent statistical reports continue to show this trend (UWI, 2019a, 2019b). It approximated 9 % during the academic years 2013-2019. This loss of diversity diminished the richness of student and staff experience, since diversity enhances thought processes, communication skills and better prepares graduates for work in pluralistic work environments (Gurin et al., 2002). However, to the best of the author's knowledge its underlying causes have not yet been investigated. Although there seems to be a combination of factors ranging from a change in UWI's governance structure in the mid-1980s (Sherlock and Nettleford, 1998), the emergence of the University of Technology, Jamaica, and a greater appeal of universities in North America are most likely contributing factors.

In parallel with the above-mentioned decrease in regional diversity, there was an increase in the number of female undergraduate students in the department. In the author's observation, it increased from less than 10% in 1972 to approximately 50 % in 2001. Such an increase is now the norm: e.g., during the academic years 2013-2019 females constituted approximately 67% across the St. Augustine campus, and 30 % in its faculty of engineering (UWI, 2019a, 2019b). From a gender equality point of view this was/is a positive development and augurs well for female empowerment in a modern society.

In the author's recollection, and from a qualitative perspective, the before-mentioned increase in the ratio of female undergraduate students brought to the fore greater diligence and superior academic performance of female students, in general. Such a difference in the academic performance between male and female university students has also been observed elsewhere, for example in Turkey (Dayıoğlu and Türüt-Aşık, 2004,) and in the Netherlands (Verbree et al., 2022). Indeed, a study of university students in the Netherlands posits greater female conscientiousness as a predictor of the gender gap in academic achievement.

7. Teaching and Learning: Quality Assurance

An enduring aspiration of the department, since its inception in 1961, has been its pursuit of excellence in teaching and learning. Against this and considering the geographic isolation of The UWI (from the north Atlantic academic stream, and within the Caribbean region due to language barriers - Dutch, French, and Spanish), triennial visits of external examiners from the United Kingdom (UK) and elsewhere were instituted in its formative years. Subsequently, a number of professors – J.R.D Francis and Peter Wolfe from Imperial College, Duncan Mara from the University of Liverpool, Paul Johnstone from the University of Dublin, D.M. McDowell from the University of Manchester, Kuldeep Virdi from the City University in London, and Johann Atrops from the University of Cologne in Germany – visited the department. They interacted with staff and students, examined coursework, and took part in oral examinations. In addition, draft examination question papers and a sample of marked scripts were sent to the aforementioned external examiners for their review. In the mid-1980s Professor Atrops recommended a system of peer review in the department as a tool for continuous improvement. This was done in the subsequent years with its attendant benefits. Other external examiners stressed the link between teaching and research and spoke of the need for a greater research output in the department. These external interactions provided beneficial checks and balances.

The department also strived for a hallmark of international recognition of its degree programme. For this purpose, in 1972, the department had its first accreditation visit by the Council of Engineering Institutions (CEI) in the UK. The CEI gradually transformed into the Engineering Council in 1981 (Chapman and Levy, 2004), and the subsequent accreditations in 1983, and 1988 took place under its auspices; and in 1993, 1997 and 2001 through its Joint Board of Moderators (https://jbm.org.uk).

A recommendation of the 1988 accreditation visit was for design to be a continuous learning thread in the curriculum. This was done and the subsequent accreditation visits consistently singled out its capstone design project for its excellence (Shrivastava, 2013). Needless to say, preparation for accreditation visits – documentation, planning and curriculum restructuring through the changing paradigms of 'Standards and Routes to Registration' (SARTOR) and the UK Standard for Professional Engineering Competence (UK-SPEC) – were one of the onerous duties of its head of department.

Perhaps, the best indicator of the quality of teaching and learning imparted at an educational institution is informal feedback from its alumni. During the past four decades, it has been the author's privilege to meet several past students informally during his travels, and in

seminars and conferences. It was uplifting to see former students running successful engineering consultancy firms, managing large construction projects, rising to senior positions in the public sector, and progressing in academia.

Four examples convey the essence of the feedback:

1) 'Coming to The UWI St. Augustine from Dominica was an exhilarating experience. Amongst the students from different islands, I understood what it means to be a West Indian, and Compton Deane taught me the value of working from first principles' (Jerry Medford, Class of 1976, Personal Communication, 2019);
2) 'Professor Phelps apart from teaching Environmental Engineering, took time to correct my grammar and instilled in me a lifelong aspiration to write clearly, concisely, and correctly. It has done me good' (Fazir Khan, Class of 1984, Personal Communication 2022);
3) 'My final year design project on a Pelton Turbine for a hydro-electric plant in Tobago remains an important formative influence' (David Prevatt, Class of 1985, Personal Communication 2022); and
4) 'When I went to the University of Birmingham in the UK to do my Master's, I had apprehensions. Would I be able to cope? I need not have worried. UWI had prepared me well' (Adesh Surujnath, Class of 1995, Personal Communication 2022).

8. Administrative and Technical Staff

Last but not least, the invaluable contribution of administrative and support staff is acknowledged. In this context, Angela Crichlow (Departmental Secretary, 1971-2008) is foremost, followed by Rohana Rafeek (Secretary of CE&M MSc Programme, 1982-2018). Similarly, the following technicians are acknowledged: Computers (Ronald Singh), Environmental (Althea Richardson), Fluid Mechanics (Sherry Ann Dumas-Harewood; Kurt Fereirra) Geotechnical/Highways (Samuel Ames, Carlyle Christian), Geology (Chatergoon Kanhai), and Structures (Darnley De Four, Martin Moore; Austin Rodriguez).

9. Revisiting the First Decade (1961-1971)

Ten years have elapsed since an account of the department's formative decade was published (Ellis and Shrivastava, 2013), and this paper provides an opportunity to include some observations which were inadvertently overlooked. The observations of Tony Gibbs (personal communication 2014 and 2022) are invaluable (*Annex B*). He is an outstanding civil engineer and a Caribbean icon (https://icons.niherst.gov.tt/icon/tony-gibbs-ci2/).

Besides, Eng Gibbs' links to the department literally go back to its roots: he was the Assistant Site Engineer with Norman and Dawbarn (Architects and Engineers) during the construction of the Faculty of Engineering buildings at St. Augustine in 1961. Specifically, his observations enhance the value of the said publication by presenting opposing views for a balanced perspective.

10. Conclusion

During the three decades, 1972-2001, the department underwent considerable expansion, physical relocation, renovation, rebranding, restructuring and an increase in the percentage of female students. Added to these were a decline in regional diversity of its students, which reduced the richness of academic experience for students and staff alike, and emergence of computers with their own positive and negative impact on teaching and learning. That the department met these challenges with resilience is a tribute to its good leadership and dedication of its staff.

The department emerged stronger to face the challenges of the new millennium, such as the need to provide a 'Matching Section' by either adding a year to its three-year BSc programmes leading to a MEng or providing an accredited MSc programme for meeting the evolving accreditation requirements of the UK Engineering Council. Chronicling how this was achieved and other subsequent changes is, in the author's view, best left for others who came to the department after him.

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Declarations:

Some documents, particularly for the years 1970-1990, could not be found. This historical note is considerably based on the recollections of the author who spent thirty-six years in the department: 1972-1975 as a graduate assistant, and 1982-2015 as a member of its teaching staff.

***Annex A*:** UWI Experimental Catchment Research Project

It became evident in the early 1980s that the volume of rainfall runoff on the St. Augustine Campus was increasing rapidly, judging from the observations of flow entering and exiting the pond between the blocks 1 (now the K. S. Julien Building) and Block 2 (now, the I. D. C. Imbert Building). It was believed an increase in impervious area on campus due to the conversion of hitherto green spaces by new buildings (such as, the International Relations Building, expansion of the Frank Stockdale Building, Management Studies Building and expansion of the car park at the main administration building as well of the tennis courts were contributing factors).

In 1984, the late Professor Harry Phelps asked the author to carry out a drainage study of the St. Augustine Main Campus (Approximately 20 Hectares) which drained into the Engineering Pond. Its objective was to initiate measures to reconfigure the drainage network, lest flooding occurs in the Faculty of Engineering located at the downstream end of the said campus. Accordingly, a Parshall Flume was constructed and equipped with a streamflow recorder (see Figure A1). Simultaneously, a recording rain-gauge was installed nearby for rainfall/runoff correlation.

In 1990, a report was prepared and submitted to Campus Research Grants Committee which had funded the project. Unfortunately, this report was not published, and neither can now be located. Nevertheless, the following summary of the author's recollection may be pertinent now.

Figure A1. Parshall Flume and Streamflow Recorder on a drain between the Principal's Office and the Swimming Pool (Photo Credit: the author – shown in the picture with his daughter, 1986)

After analysing five years of concurrent rainfall and streamflow measurements it became obvious that a runoff from the campus had fundamentally altered. That is to say, runoff from areas outside the campus (i.e., north, and east of the campus) was entering, as observed during storms. Moreover, anecdotal evidence of flow through the Engineering Pond indicated that the campus internal drainage network was self-contained until the end of the 1970s. Subsequent flooding of the International Relations Building, of some of the Faculty of Engineering Laboratories and other areas on the campus reflects a new reality. It also tells us that any solution to the flooding problems on the St. Augustine Campus should consider the growing urbanisation of external areas as well.

***Annex B*:** Observations of Eng. Tony Gibbs, Fellow, Royal Academy of Engineering

• "Although the building and design of bridges and the design and maintenance of waterworks are indispensable parts of modern life, the role of a Civil Engineer remains somewhat obscure to many people. If this is so today, it was even more so in the 1950s and 1960s, when the Civil Engineer was even more an enigmatic character on the West Indian landscape." – When I embarked on my engineering studies in 1957 and when I worked in Trinidad in 1961-1962, I was not conscious that engineering was an obscure profession nor was I conscious that I was perceived as an enigmatic character.

• "In fact, as many engineers who began their studies or careers in the 1960s would explain, to the average West Indian, the engineer was simply "an Englishman," "a white man", and as

such, his mystique, in the social milieu of the last days of colonialism, was heightened (Phelps, 2007; Julien, 2008; Suite, 2007)." – The engineers I recall from my 1961-1962 stint in Trinidad included Harry Phelps, Curtis Knight, Ron Bates, Roderick Douglas and David Key. Of those, only Key was a white Englishman. Curtis Knight, a Grenadian, was regarded as arguably the top civil engineer in Trinidad at that time. And it was he who initiated the formation of APETT. Roderick Douglas. too, was a Grenadian. It may be that Grenadians had a different perspective on the profession. When I was President of the Barbados APE in 1973-1974, my First Vice President was Grenadian Ambrose Johnson, and my Second Vice President was Grenadian Bert Mahy.

• "… United Nations Educational, Scientific and Cultural Organisation (UNESCO) put it, "that too few returned to their homes to practice what they had learned" (UNESCO, 1969, p. 10)." – I am surprised at that. I can think of only one Caribbean engineering student that I knew during my 4-year undergraduate period in the UK who did not return to work in the Caribbean.

• "The Faculty was funded by the Ford Foundation (Buildings)…" – I do not think this is correct for the first engineering buildings at St Augustine. The Ford Foundation buildings came much later. Also, while I was working at St Augustine in 1961-1962 my firm (Norman and Dawbarn) were busy designing Canada Hall. I doubt very much that Ford Foundation funded that project.

• "A strong example of this is the Jentech Consultants Limited engineering company of Jamaica. This company was founded in 1972 by five (5) men who were cohorts and friends at the Faculty of Engineering." – My recollection is that Dr. Radcliff Frederick, a Trinidadian who was not a graduate of The UWI, was one of the founding partners of Jentech. Radcliff was a top-class geotechnical engineer. I was quite friendly with him during my working period in Jamaica in 1965. You may wish to check this with Wayne Reid.

• "UNDP analysts feared that this compromised the prime objective of the Department: to create well-trained and qualified regional engineers." – Surely not – surely the prime objective of the Department is to create well-educated graduates who are subsequently trained to become professionally-qualified engineers equipped for work anywhere in the world.

• "Dr. Selvanayagam's area of specialisation was structural engineering. He had obtained his PhD at Imperial College in London in 1950, where he had worked on analytical and experimental investigation of the distribution of stress in shell structures." – It is a pity he did not work much more in that field while at UWI. Shell structures have an important utilitarian role in the construction of a wide variety of buildings – warehouses, factories, schools, housing, stadiums, and auditoriums. In the Commonwealth Caribbean, probably the majority of shell (and folded-plate) concrete structures were designed by Wilson Chung and Fred Benghiat (in Jamaica); David Key, Anthony Farrell and Tony Gibbs (in Trinidad); Tony Gibbs (in Barbados); Anthony Farrell, Tony Gibbs and Wilston Etienne (in Dominica). Of those engineers, only Anthony Farrell graduated from UWI, and he did not learn about shell structures there. Shells and folded plates are favourable for earthquakes, hurricanes and climate change mitigation and adaptation. And they are economical.

• "Late Emeritus Professor I.D.C. Imbert (1931-2009)" – I believe that Desmond Imbert's funeral was on 26 May 2010. I recall asking a gathering of 100 engineers, scientists, architects and insurance personnel attending a seismic hazard meeting at the Normandie Hotel to stand for one minute's silence in honour of Desmond on that day.

• "In this regard, the 1970s represented a boom for the Department of Civil Engineering. The main reason for this boom was the success of Trinidad's oil industry, as well as Jamaica's bauxite and tourism industries. …. Jamaica, one of the countries providing subventions to the University was developing profitable bauxite and tourism industries. … the number of projects requiring the services of a civil engineer in Jamaica and Trinidad and Tobago was increasing at a rapid pace." – The 1970s saw the collapse of the very strong engineering profession in Jamaica. At the start of the 1970's Jamaica boasted a construction industry – engineers, architects, and builders – unmatched in the rest of the Caribbean. By the end of the 1970's the construction industry had been decimated. In fact, it still has not recovered its former glory.

Author's Biographical Notes:

Gyan Shrivastava *retired in 2015 as a Professor of Coastal/ Environmental/Water Resources Engineering in the Department of Civil and Environmental Engineering at The University of the West Indies. He received his education in Civil Engineering at the Indian Institute of Technology at Kharagpur, and Delhi, Imperial College in London, and The University of the West Indies. He is a Member of the Institution of Civil Engineers in London, and a Chartered Civil Engineer.* ■

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