STRESS-STRAIN CHARACTERISTICS OF CONCRETE CONTAINING ITAKPE IRON ORE TAILINGS

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DEPARTMENT OF CIVIL ENGINEERING

FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY MINNA, NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING IN CIVIL ENGINEERING

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DECLARATION

I hereby declare that this thesis titled: "**Stress-Strain Characteristics of Concrete Containing Itakpe Iron Ore Tailings**" is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

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CERTIFICATION

The thesis titled: "**Stress-strain characteristics of concrete containing Itakpe Iron ore tailings**" by: **AKILU, Muhammad Aminu** (MEng/SIPET/2018/8835) meets the regulations governing the award of the Degree of Meng. Civil Engineering (Structures option) of Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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DEDICATION

This research work is dedicated firstly to the Almighty Allah for his glorious and unceasing support in all my endeavours, and to the beloved prophet Muhammad (S.A.W.), my lovely Parents and wonderful family and friends around the world.

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ABSTRACT

Natural sand has been the conventional fine aggregate in concrete production for many decades. However, due to the depletion of sand which is prone to erosion there has been need for alternative materials suitable to replace sand in concrete. In this research Itakpe Iron Ore Tailings (IIOT) was used as partial replacement of fine aggregate in concrete production. The IIOT was obtained from different locations at the tailings dump sites of National Iron Ore Mining Company (NIOMCO) in Itakpe, Kogi State, Nigeria. Sieve analysis, Specific gravity, Bulk density, Moisture content, AIV and ACV tests were carried out on the aggregate and slump test was carried out on fresh concrete containing the IIOT. Three concrete specimens were prepared from a mix of designed strength 25N/mm^2. IIOT was used to replace fine aggregates from 0 % to 20 % in steps of 5 %. Concrete cubes measuring 150 mm x 150 mm x 150 mm were cast and their densities and compressive strengths evaluated at 3, 7, 14, 21 and 28 days of curing. The result showed IIOT concrete had higher densities than control due to the high Iron (Fe) content, while 20 % IIOT had higher compressive strength than 0 % (control) in concrete at 28 days and was considered the optimum but 5 % and 15 % were very close. The relation between compressive strength and compressive strain was attained from the stress-strain curve (SSC) for various replacements of sand. The SSCs for concrete with IIOT showed higher maximum strains, 23.08 % lower than those of conventional concrete. The secant modulus of elasticity (MoE) of concrete was determined from the SSCs at 28 days only and the MoE increased as sand replacement increased. The modulus of elasticity was from 13,700 N/mm^2 to 28,700 N/mm^2 having 20 % IIOT replacement as the highest. Based on the characteristics of the SSCs, the structural design process of concrete with IIOT within the elastic and inelastic range can be carried out without need of modifications. The findings of this research showed there is a potential towards utilization of IIOT in construction applications and can serve as a normal aggregate alternative for future use. Tailings promote the preparation of eco-friendly IIOT concrete and provide a new way to use waste resources.

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ABBREVIATIONS, GLOSSARIES AND SYMBOLS

ACI	American Concrete Institute
ACV	Aggregate Crushing Value
ASTM	American Society for Testing and Materials
AIV	Aggregate Impact Value
BS	British Standard
Gs	specific gravity
IIOT	Itakpe Iron Ore Tailings
W	Weight
PLC	Portland Limestone Cement
ρ_b	Bulk density
M C	Moisture Content
SSC	Stress-Strain Curves

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of Study

Concrete is one of the engineering materials commonly used in building components. Concrete is the most versatile heterogeneous or composite construction materials and an impetus of infrastructural development of any nation. Many Civil engineering practices and construction work around the word depend largely on concrete. Concrete is a synthetic construction material made by mixing cement, fine aggregate, coarse aggregate and water in a specified proportion. Sand as fine aggregate is more extensively consumed in concrete construction. Therefore, many developing countries are currently grappling with the challenge of meeting the growing demands for infrastructural development due to the shortage of natural sand. In this regard, sand could be replaced by different waste materials, which might be able to improve plasticity, workability, and increase concrete strength to enhance durability (Yisa *et al.*, 2016).

Natural sand has been the conventional fine aggregate in concrete production for many decades. However, there has been extensive research into alternative materials suitable to replace sand in concrete. The need to find replacement for sand stems from the fact that in most parts of the world, there is growing concern about the depletion of sand deposits, environmental and socio-economic threats associated with extraction of sand from river banks, coastal areas and farm lands (Aditya and Lakshmayya, 2016). Some alternative materials which have been studied for use as partial replacement for sand include fly ash, slag limestone, silica stone, furnace bottom ash and recycled fine aggregate (Siddique, 2003).

The increasing demand for heavy construction material like steel and iron has resulted in the establishment of many iron ore mining companies. Iron ore tailing is a waste generated from the iron ore industry. It is a very fine aggregate residue resulting from the extraction of iron from iron ore. The residue left after extraction is in the form of slurry (Prema Kumar *et al.*, 2014). Usually, the ore tailing is disposed in the vicinity of plant as waste material over several hectares of valuable land leading to water and land pollution. Large quantities of iron ore tailing are generated every year leading to environmental pollution and disposal problem. (Chen and Li, 2012) Lots of iron ore tailings has been accumulated in China, which brought severe environmental pollution and took up the massive land, and even threatened the life safety of people. By the experimental study, it is found that in north area of China, iron ore tailing is easy to be grinded and burned which may be used as the sand with good particle gradation.

Iron tailings stand as prominent by-products from mining operations, constituting a substantial portion of industrial solid waste. With the advancement of the steel industry, the proportion of iron tailings in industrial solid waste has steadily risen. The extensive buildup of iron tailings leads to the wastage of valuable land resources and presents substantial threats to the nearby ecological environment (Liu *et al.*, 2023).

Yisa *et al.* (2016) As the world is becoming environmentally conscious, a variety of other waste materials have been used to replace sand in concrete to find solutions and measures to counteract the problem of poor performance of concrete. Clever utilization of diverse waste materials as substitutes for sand in concrete not only mitigates the issue of concrete's suboptimal performance but also aligns with global efforts towards sustainable construction practices, marking a significant stride in the ongoing journey toward a more eco-friendly and resilient infrastructure landscape.

Over the years, several research have been carried out on the utilization of iron ore tailings as aggregates and cement replacement in concrete production for several place such as mortar production, light weight concrete, ultra-high-performance concrete and quick high durability concrete. It is a prime concern to researchers on the effective utilization of iron ore tailings as partial replacement of fine aggregate and cement in concrete. While considerable amount of research has been conducted to study the rheology, strength and durability properties of concrete, no work has been carried out on the stress-strain characteristics of concrete with IOT. There is therefore the need to study the strength and stress–stress characteristics of concrete with IOT.

Iron ore tailings (IOT) deposit of Itakpe mines in Okehi LGA, Kogi state, Nigeria was used as partial replacement of fine aggregate to investigate the impact on the stress-strain characteristics of concrete. The research was prompted by the abundant availability of iron ore tailings in the local environment. By incorporating this readily available material into the concrete mix, the study aimed to assess how it influences the structural properties of concrete. Investigating this abundant source of iron ore tailings not only addresses environmental concerns related to their disposal but also presents a potential sustainable solution for the construction industry, contributing to both eco-friendly practices and effective infrastructure development.

1.2 Statement of the Research Problem

Numerous developing countries have nowadays faced a struggle in providing the quantity of natural sand so as to encounter the enhancing desires of infrastructural development in recent years. In recent years, steel production has increased significantly to meet the construction industry demands. In some areas, river sand resources, an important raw material for the preparation of concrete, have been in short supply. Excessive exploitation of natural river sand will inevitably lead to severe damage to farmland and river courses, which will cause desertification and degradation of the ecological environment. In recent years, aeolian sand has attracted attention as a new type of building material and has been widely used in highway and water conservancy projects in desert areas (Elipe and López-Querol, 2014).

The increased still production led to the generation of huge amount of iron ore tailings (IOT) which are disposed of as waste in landfills, quarries, rivers, oceans. These tailings contain toxic heavy metals which pollute the environment, water and soil at abandoned copper mines and waste sites. IOT is a waste product generated from the processing and mining of iron from its ore (Itodo *et al.*, 2017). Mining of iron sites are located at Itakpe in Kogi, where iron ore is in abundance in several million metric tons. Itakpe which was designed to process 24,000 tons of iron ore in 24 hours produce IOT in excess of 3000 tons as waste per day (Ajaka, 2009; Uchechukwu and Ezekiel, 2014).

1.3 Aim and Objectives

The Aim of this study is to determine stress-strain characteristics of concrete containing iron ore tailings as partial replacement of sand. To achieve the aim of the study, the objectives considered are;

i. to determine the physical properties of the constituent materials
ii. to determine workability and compressive strength of the concrete with IIOT as partial replacement of sand
iii. to determine the stress-strain of the concrete and its secant modulus of elasticity at 28 days

1.4 Justification

There is increasing demand for heavy construction material like steel and iron has resulted in the establishment of many iron ore mining companies. Iron ore tailings is a waste generated from the iron ore industry. In this regard, sand could be replaced by different waste materials, which might be able to improve plasticity, workability, and increase concrete strength to enhance durability.

These tailings pose serious environmental problems besides occupying large area of landfill sites. One way of disposing these IOT is to utilize them in construction industry where they would be recycled and reused to produce green and sustainable product. It would also save landfill space and decrease the extraction of natural raw materials. Tailings must be managed to optimize human safety and environmental protection.

The global demand to reduce the increasingly high cost of waste disposal and conserve raw material has led to intense global research towards economic utilization of waste for engineering purposes. The successful utilization of iron ore tailing (IOT) as fine aggregate would turn this waste material into valuable resources, reduction in the strain on the supply of natural sand, and economy in concrete production.

Hence, there is a dire and urgent need to explore alternative materials to replace river sand as fine aggregate in concrete. Utilizing IOT as a sand replacement in concrete not only minimizes environmental problems, cost, and natural resources depletion but also offers a viable solution to the pressing need for sustainable construction practices (Shettima *et al.*, 2016).

The use of wastes and by-products as concrete aggregates is of great practical significance since they often constitute as much as three-quarters of the concrete by volume. However, there is a great need to improve the physical properties of fresh and hardened concrete through modification in its constituents which in turn leads to appreciate Klink (1975) ion of the mechanical properties of hardened concrete.

While considerable amount of research has been conducted to study the rheological, strength and durability properties of concrete, no work has been carried out on the stress-strain characteristics of concrete with IOT. There is therefore the need to study the strength and stress–stress characteristics of concrete with IOT.

1.5 Scope of Research

The scope of this research involved the collection of samples. Determination of physical and mechanical properties of aggregate which include sieve analysis, moisture content, specific gravity, bulk density, aggregate impact value, aggregate crushing value, slump of concrete, compressive strength using cube size 150mm x 150mm x 150mm for curing and crushing at 3, 7, 14, 21 and 28 days respectively for 0, 5, 10, 15 and 20 % IOT respectively, determination of stress-strain of hardened concrete at 28 days only and determination of Secant modulus of elasticity of concrete at 28 days.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Preamble

Concrete is the basic material in all construction works. Concrete is a solid mass made by use of a cementing medium, generally the ingredient consists of cement (binder), fine aggregate (sand), coarse aggregate (gravel) and water. Concrete is a construction and structural material consisting of hard, chemically inert particles substance known as aggregate such as sand and gravel, that is bonded together by cement and water (Abdullahi, 2006; Abdullahi *et al.*, 2013).

Aggregate with good quality must be clean, hard, strong, durable particles and be free of contaminate material that can affect hydration of cement or reduce the paste aggregate bond. Aggregate as a natural occurring material will most time consist weathered or unstable particles in the deliver product. Sieve analysis test will allow the percentage passing of size required such as 10 mm, 20 mm 40 mm for coarse aggregate or to be (retained on a No. 4 sieve) the one passing through (No. 4 sieve) is known as fine aggregate. Aggregate can be classified into two types, such as fine aggregate and coarse aggregate.

Ordinary Portland Cement (OPC) serves as the primary component for concrete production, leading to a growing demand for cement. In the cement manufacturing process, clinker is heated at approximately 1,450 ^{0}C (Neville, 2000).

The compressive strength of aggregate is a crucial factor in the selection of aggregate. Most aggregate are several times stronger than the other element in concrete when determine the strength of normal concrete, are therefore not a factor in the strength of normal concrete. Before the execution of mixing of concrete, the physical and mineralogical properties must be known to obtain a desirable mixture. These include size gradation, texture, moisture content, specific gravity, bulk unit weight and shape. The strength, workability and durability of concrete is determining by properties which include size gradation, texture, moisture content, specific gravity, bulk unit weight and shape along with water/cement ratio.

The properties of fresh concrete are affected by shape and texture of the aggregate more than the hardened concrete. When smooth and round aggregate is used instead of rough angular or elongated aggregate it makes concrete to be more workable. Angular and elongated aggregate are produced from crushed aggregate, which have a higher surface to volume ratio, has better bond characteristics but require more cement paste to produce a workable mixture.

When developing the water/cement ratio the moisture content is an important factor to be put into consideration. Base on the porosity of the particles and the moisture condition of the storage area all aggregate will contain some moisture content. The various related concerns which lead us to the way of sustainable development that are mentioned below (Meyer, 2009):

i. Previous mistake could be cured by purifying the polluted water and soil.
ii. Reducing the global warming by neglecting the contamination of air, water and soil, as well as CO_2 emission.
iii. Balancing between consumption and generation of natural resources (material or energy).

Striving for a balance between economic advancement and environmental conservation is essential. This involves improving social life and living standards while minimizing disruption to the environment as much as possible.

Incorporating industrial and construction waste into concrete production offers a sustainable approach, conserving natural resources and promoting environmental protection. Consequently, investigating the bonding characteristics of green reinforced concrete, as well as its performance after exposure to fire, becomes imperative in this context (Zhu *et al.*, 2023).

2.2 Concrete

Concrete is an assemblage of cement, aggregate and water. The most commonly used fine aggregate is Sand derived from river banks (Lohani *et al.*, 2012). Concrete is one of the most widely manufactured materials in the world and over recent decades technical innovations, especially in the use of admixtures have improved not only the quality but also the range of potential applications for this versatile construction product. Today's concrete must fulfil a wide range of requirements in both the fresh and hardened state. In most cases the properties of fresh concrete also affect the quality of the hardened concrete and ultimately its durability. (Fabunmi *et al.*, 2016). These effects would all lead to reduced quality and durability of the hardened concrete.

There are many types of concrete which include the following; - Self-compacting concrete, Reinforced concrete, Prestressed concrete: pretensioned (precast) concrete and post-tensioned concrete, High performance concrete, High strength concrete, Modified-density concrete. After understanding the diverse types of concrete available, it becomes crucial to choose the most suitable one for specific construction needs. Each type possesses unique properties and applications, allowing for tailored solutions in various construction projects (Gonzalez *et al.*, 2020).

According to Ayhan and Gökçe (2012), the main issue in working with fresh concrete is the workability during filling of formwork. One of the problems found in workability is occurrence of segregation depending on water cement ratio (w/c ratio). Segregation is strongly related to w/c ratio.

2.3 Aggregate

Aggregate is very crucial in concrete mix, is thoughts as inert filler within a concrete. It plays a very important role and influence the properties of both fresh and hardened concrete. The character and performance of the concrete can be change due to change in gradation, maximum size, unit weight and moisture content. In a concrete mix, aggregate occupied about 70 % to 80 % of the volume of concrete, so to obtain consistent concrete strength, workability and durability, aggregate must be properly selected to be durable, blended for optimum efficiency and properly controlled (Mehta and Monteiro, 2014).

Recycled Aggregate Concretes (RAC) are defined as concrete using recycled aggregates or recycled aggregates in combination with natural aggregates and can be either of fine or coarse sizes. Recycled aggregates are typically not used in new concretes past a certain percent replacement due to the negative influence on compressive strength, modulus of elasticity, shrinkage, and creep. This negative influence is generally attributed to the presence of old mortar which adheres to recycled aggregates. Performance of recycled aggregates greatly depends on the quality and quantity of this adhered mortar (Etxeberria *et al.*, 2007). Recycled aggregates from pre-cast or reinforced concrete structures made with high-strength concretes have been shown to perform better as a recycled aggregate for new concrete. Quantity of adhered mortar depends on the original w/c ratio of the concrete and crushing technique used (Yang *et al.*, 2008; Chakradhara Rao *et al.*, 2010).

Gabriel Bastidas-Martínez *et al.* (2022) demonstrated that incorporating Iron Ore Tailings (IOT) into Hot Mix Asphalt (HMA) enhances its mechanical properties without raising mixing and compaction temperatures or requiring higher quantities of asphalt binder. This finding not only improves the efficiency of IOT utilization but also offers an environmentally friendly method for their disposal.

2.4 Iron Ore Tailings in Concrete

Iron Ore Tailings is a waste product generated from the processing and mining of iron from its ore. Ponds are utilized for disposal of tailings. Iron ore is being beneficiated around the world to meet the raw materials requirements of the iron and steel industries. Iron ore has its own peculiar mineralogical characteristics and optimum product extraction at any site requires tailoring of the metallurgical treatment and specific beneficiation process selection for use. The choice of beneficiation technique depends on the nature of the gangue and its association with the ore structure.

The prime function of beneficiation of iron ore is to improve the content of the finished iron. Beneficiation proceeds mainly from washing, sizing by classification, jigging and then magnetic separation (Mohanty *et al.*, 2010). The iron ore tailings are also contaminated with parts per million levels of heavy metal ions such as Cu, Pb, Zn, Cr, Ni, Mn and U, as well as lower levels of macronutrients. Many of these potentially toxic elements reach and become pollutants of water (Itodo *et al.*, 2017).

Adebimpe and Fatoye (2021) conducted the chemical characterisation of Itakpe Iron Ore Tailings, indicating the two major components Silicon Oxide (SiO_2) and Iron (Fe). The SiO_2 with the highest composition of 71 % while, Fe consisting of 15 % and other various compounds as shown in Table 2.1.

Table 2.1: Chemical composition of Itakpe Iron Ore Tailings

S/no	Component	Value (%)
i	SiO_2	71
ii	Al_2O_3	2.62
iii	Fe(total)	15
iv	TiO_2	0.2
v	CaO	1.2
vi	MgO	0.3
vii	P	0.08
viii	S	0.06
ix	Total Alkali (Na_2O + K_2O)	1.2

Source: Adebimpe and Fatoye (2021)

The Itakpe iron ore deposit has a reserve of about 200 million tonnes with an average iron ore content of 36 %. Itakpe iron ore processing plant produces a waste material of about 64 % of its capacity (Ajaka, 2009). Soframines (1987) showed that the Itakpe project was designed to treat a minimum of 24,000 tonnes of ore per day and operate 300 days per year. The waste to ore ratio is 4:1 (Adebimpe and Akande, 2011). If the tailings are not disposed of, the land will be seized, the environment will be polluted, and the useful resources cannot be fully used. Mining of iron sites are located at Itakpe in Kogi, where iron ore is in abundance in several million metric tons. Itakpe which was designed to process 24,000 tons of iron ore in 24 hours produce IOT in excess of 3000 tons as waste per day (Ajaka, 2009; Uchechukwu and Ezekiel, 2014).

Itakpe iron ore deposit has a reserve of about 200 million tonnes with an average iron ore content of 36 %. This has to be beneficiated at a rate of 8 million tonnes per year to produce 64 % Fe concentrate as sinter material for the Ajaoukuta blast furnace and 68 % Fe concentrate as pellet feed for the direct reduction plant at Aladja, in Nigeria. At this production rate, large quantities of tailings are obtained as waste product of the beneficiated iron ore. It is estimated that the stripping ratio (waste/ore ratio) of the deposit would amount to approximately 28 million tons (Ugama *et al.*, 2014).

Kumar *et al.* (2006) demonstrated the usage of fly ash, blast furnace slag and iron ore tailings in the preparation of floor and wall tiles. It was concluded that partial addition of iron ore tailing, fly ash and blast furnace slag in suitable combination in ceramic tiles will improve its scratch hardness (>6 on Mohr 's scale) and flexural strength (>25 MPa).

The experiment carried out by Jian *et al.* (2011) on sintered wall materials reveals that the iron ore tailings and waste can be used very effectively as construction material. The study also showed that due to higher iron content in iron ore tailings and waste rock, the products reduce the sintering temperature and decreased energy consumption.

Experiment were conducted to determine the suitability of iron ore tailings (IOT) as fine aggregate replacement of sand (RS) for concrete used for rigid pavement (Ugama *et al.*, 2014). This study assessed the integration of Iron Ore Tailings (IOT) into hot mix asphalt type C (HMA-C). Specifically, IOT was utilized as a filler, constituting 1 % of the total mass of HMA-C (Gabriel Bastidas-Martínez *et al.*, 2022).

Zhao *et al.* (2014) investigated that 100 % replacement of natural aggregate by the tailings significantly decreased the workability and compressive strength of the material. Also showed, when the replacement level was no more than 40 %, for 90 days standard cured specimens, the mechanical behaviour of the tailings mixes was comparable to that of the control mix, and for specimens that were steam cured for 2 days, the compressive strengths of the tailing's mixes decreased by less than 11 % while the flexural strengths increased by up to 8 % compared to the control mix. Concluded stiffness and hardness of the tailings were on average lower than those of the natural sand. Incorporation of the tailings into the mix increased the water demand and lowered the flow ability of the fresh material due to the high specific surface area and rough surface of the tailings.

Huang *et al.* (2013) used iron ore tailings powder as cement replacement for developing green ECC (Engineered Cementitious Composite) and concluded that the replacement of cement by less reactive Iron ore tailings in ECC reduces the matrix fracture toughness. Increasing the replacement of cement beyond 40 % replacement ratio reduces the compressive strength of ECC. Iron ore tailings in powder form are used to partially replace cement to enhance the environmental sustainability of ECC. Mechanical properties and material greenness of ECC containing various proportions of IOTs are investigated. The replacement of cement with Iron ore tailings results in 1,032 % reduction in energy consumption and 29–63 % reduction in carbon dioxide emissions in green ECC compared with typical ECC. may include coarse and fine particulates in the wash water, and these particulates may form a slurry known as wet tailings.

In recent decades, intensive research and development efforts have been directed towards finding cost effective and eco-compatible solutions for minimizing and utilizing the waste produced in iron-ore mining operations (Johnson *et al.*, 1994; Bandopadhyay *et al.*, 2002). Bai *et al.* (2011), stated that the fine particles less than 75 μm in iron ore tailing sand are beneficial to the reduction of expansion induced by alkali- silica reaction (ASR) in concrete and mortar. According to (Costa and Adriana, 2010), IOT is described to be innocuous based on the quantity of dissolved silica and reduction in alkalinity of the mix.

It was reported that the use of waste materials in concrete products will lead to sustainable concrete and greener environment (Aggarwal and Siddique, 2014; Anastasiou *et al.*, 2014). Senthamarai and Manoharan (2005) reported that the industrial and other wastes used in concrete-making will improve concrete properties and reduce cost. Growth in construction industries and the consequent increase in consumption of natural fine aggregate dwindle the natural resources. This increased in the consumption of river sand for construction activities means that the riverbeds are being over-exploited. This leads to a range of problems which include increased river bed depth, water table lowering, intrusion of salinity and destruction of river embankment (Shettima *et al.*, 2016).

Liu *et al.* (2011) conducted a research study focused on sprayed concrete incorporating Iron Ore Tailings (IOT). In their experiments, natural sand was replaced with IOT of up to 100 % and obtained strength of 23.4 MPa at 28 days.

Zhao *et al.* (2014) studied the possibility of using IOT to replace natural aggregate to prepare ultrahigh performance concrete. They reported that 100 % replacement of natural aggregate with the tailings significantly decreased the workability and compressive strength of the concrete. This submission contradicted the study by Uchechukwu and Ezekiel (2014) on the evaluation of IOT in concrete. Their investigation indicated that the use of IOT increased the compressive strength of concrete either as sand or cement replacement but better performance was recorded for cement replacement.

Das *et al.* (2000) studied the use of IOT to develop ceramic tiles and their study showed, that tiles produced at a maximum of 40 % of IOT were superior in terms of scratch hardness and strength, compared to European standard specifications. Kuranchie *et al.* (2014) studied the utilisation of Iron Ore Tailings (IOT) in the production of geopolymer bricks. Their results indicated that, the geo-polymer brick cured for seven days had superior characteristics than ASTM C62 (2013) standard requirements for building brick.

Utilized Iron Ore Tailings (IOT) in the manufacturing of concrete paving blocks and observed that the compressive strength of these blocks, containing IOT, surpassed that of blocks made with sand only (Aruna and Sampath, 2010). There were slight enhancements in compressive strength, flexural strength, and elasticity modulus of concrete made with IOT (Zhang *et al.*, 2020).

2.5 Stress and Strain in Concrete

The elastic characteristics of a material are a measure of its stiffness. Knowledge of the modulus of elasticity is essential in the determination of deformation, deflection or stresses under short-term and long-term loading (Umoh and Olusola, 2012). When the deformations of the different structural elements of a structure have to be calculated, the determination of elastic properties of concrete is also very important (Demir, 2008).

Also, Myers (1999) noted that the modulus of elasticity of concrete is one of the most important mechanical properties of concrete since it impacts the serviceability and the structural performance of reinforced concrete structures. It indicated that the modulus of elasticity increases with an increase in the compressive strength; and also increased at a higher rate than the compressive strength at later ages from 120 days and above, which is more pronounced for the stress–strain relationship than for the compressive strength of concrete (Umoh and Olusola, 2012).

(Yang *et al.*, 2019) developed an analytical model to provide a stress-strain relationship for concrete brick prisms with three different mortar strengths predicted the relationship accurately, regardless of mortar strength. Some discrepancies were observed after $\varepsilon_{0.5}$ in the descending branch of the stress-strain curve but developed two separate equations for the key parameter β_1 for ascending and descending branches, separately, which is the exponential function of $(f_{pm})^{0.67}$ which defined the stress-strain curve.

When the increase of axial compression loading began, small micro-cracks gradually form in the test specimens. Cracks were observed at comparatively lower stress in concrete with 100 % sand replacement than in concretes with 0 % and 25 % sand replacement. The variation in the modulus of elasticity is the consequence of better bonding of aggregate and cement particles due to the shape, texture and grading characteristics of the quarry rock dust. (Kankam *et al.*, 2017).

Gonzalez-Corominas and Etxeberria (2014) also observed a 5 % decrease in the modulus of elasticity, although their study refers to low substitution percentages less than 30 % and uses ceramic waste to manufacture high performance concrete because this reduction was due to the lower density of the concrete derived from using ceramic waste. There is a slight decrease in the modulus of elasticity, which does not reach 6 % for a 100 % substitution with waste mining sand, so the influence of using this type of waste on the modulus of elasticity of Ultra High Performance Fibre Reinforced Concrete is negligible (Gonzalez *et al.*, 2020).

The hydrated phase assemblage of IOT samples was further proved by micro indentation which formed a denser microstructure in interfacial transition zone with enhanced bonding properties of reduced modulus of 8.13 GPa and hardness 0.44, compared to reduced modulus of 6.63 GPa and hardness 0.37 of natural aggregate samples. This is as a result of the local low water-binder ratio, interfacial transition zone of IOTs concrete showed a denser microstructure and higher micromechanical properties than natural aggregate concrete (Feng *et al.*, 2021).

Liu *et al.* (2023) studied the variations in the relative dynamic elastic modulus of concrete following dry-wet cycles. This parameter signifies a material's resistance to elastic deformation, with higher values indicating a reduced likelihood of such deformation. The study investigates how this modulus changes, mirroring the concrete's mass loss rate under identical conditions.

Liu *et al.* (2022) studied the sand replacement with IOT from 0 % to 100 % on compressive strength, splitting tensile strength and the stress strain relationship. The research findings revealed a notable increase in compressive strength when incorporating 20 % to 40 % Iron Ore Tailings (IOT) in the mix. However, any further increase in IOT led to a decline in strength. Additionally, the modulus of elasticity exhibited a significant drop from 60 %, particularly with 100 % IOT replacement, showing a decrease of 14.36% in comparison to concrete containing only sand. The British Standard range of values for Static modulus of elasticity is summarised in Table 2.2, sourced BS 8110 part 2 (1985).

Table 2.2: Static modulus of elasticity at 28 days of normal-weight concrete

Cube compressive strength f_{cu} 28 Days	Static Modulus of Elasticity E_c, 28 Days	
	mean value	Typical range
N/mm^2	kN/mm^2	kN/mm^2
20	24	18 to 30
25	25	19 to 31
30	26	20 to 32
40	28	22 to 34
50	30	24 to 36
60	32	26 to 38

Sourced: BS 8110 part 2 (1985)

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

The study focused on specific constituent materials, all of which fall within the predefined scope of the research. These materials include;

i. River Sand
ii. Itakpe Iron Ore Tailings (IIOT)
iii. Coarse Aggregate
iv. Cement
v. Water

3.1.1 River sand

The river sand used for the study was collected from River Kaduna in Kaduna metropolis, Kaduna State in Plate I. The particles used were those that passed through sieve with aperture 5 mm and retained on sieve with aperture 0.0063 mm. It was clean, sharp, free from clay and organic matter. The sieves commonly used for grading fine aggregates in BS 882 (1983) are 10 mm, 5 mm, 2.36 mm, 1.18 mm, 600 microns, 300 microns, and 150 microns. The sieve analysis of the river sand was conducted and the particle size distribution was well graded, in accordance with BS 812: part 2 (1995).

Plate I: River sand

3.1.2 Iron ore tailings

Samples of the Itakpe Iron Ore tailings (IIOT) used for this work was taken from National Iron Ore Mining Company (NIOMCO), which is located at Latitude 07°36^{1}20^{11} and Longitude 6°18^{1}35^{11} E in Okehi Local Government Area in Itakpe, Kogi State, Nigeria. The sample was thoroughly sieved (grains passing through BS sieve 5mm size) and cleaned before use to ensure that the debris and other forms of impurities that could alter the result was removed as shown in Plate II. The IIOT was close and within the range of 5 mm, 2.36 mm, 1.18 mm, 600 microns, 300 microns, and 150 microns.

Plate II: Itakpe iron ore tailings

3.1.3 Coarse aggregate

Coarse aggregate sample used was mainly gravel from crushed parent rock which was sourced from kabala junction, western by-pass, in Kaduna State. The maximum aggregate size of 20 mm with sieve sizes ranging from 20 mm, 14 mm, 10 mm, 5 mm. The physical properties of the aggregates used for the preparation of the test samples was determined in the department of Civil Engineering, structural laboratory, Kaduna Polytechnic Tudunwada, Kaduna State in accordance with BS 812: part 2 (1995).

3.1.4 Cement

Dangote brand of 3X Portland limestone cement (PLC) in 50kg sourced within Old Panteka, Sabon Gari, Kaduna, Kaduna State was used for this research, conforming to BS 12 (1996), specifications for Portland limestone cement. The PLC met the same physical and mechanical requirements as ordinary Portland cement, including setting times, compressive strength, and soundness.

3.1.5 Water

The potable water used for mixing and curing of the concrete samples was obtained from the tap at Department of Civil Engineering, Structural laboratory, Kaduna Polytechnic Tudunwada, Kaduna, Nigeria. The Tap water used for the mixing in this research was properly examined to ensure that it was clean, free from contaminants either dissolved or in suspension and good for drinking in conformity to BS 3148, (1980).

3.2 Methods

The selection was focused on specific methods, all of which fall within the predefined scope of the research. These following were adopted for this research.

3.2.1 Determination of the proportion of the aggregate

3.2.1.1 Coarse aggregate

The aggregates were graded in accordance to the British standard BS 812: part 2 (1995) using sieves analysis. Coarse aggregates with 20 mm maximum aggregate size were retained on No.4 (4.5 mm) sieve, but generally it sizes ranges from 5 mm to 150 mm using proper equipment such as mechanical sieve shaker, digital weighing balance (accurate to 0.1 % of the mass of the sample), cleaning brush, scoop and pan. The test was conducted on coarse aggregates only. The aggregate that passed 4.75mm sieve (No. 4) and predominantly retained on a No. 200 (75 µm) sieve are classified as fine aggregate.

3.2.1.2 Fine aggregate

The aggregates were graded in accordance to the British standard BS 812: part 2 (1995) using sieves analysis. Typically, 75 µm, 150 µm, 300 µm, 600 µm, 1.18 mm, 2.36 mm, 4.75 mm, 5.00 mm are the sieve sizes used for fine aggregates. The equipment used to conduct the test were mechanical sieve shaker, digital weighing balance (accurate to 0.1 % of the mass of the sample), cleaning brush, spatula and pan. The test was carried out on river sand and IOT aggregate samples only.

3.2.2 Natural moisture content

There is a variation in moisture content from one stock pile to another as a result of weather the moisture content must be determined frequently (Neville, 2000). The total water content of the moist aggregate is equal to the moisture content and absorption in the aggregate. Several methods are available but accuracy depends on sampling. BS 812 part 109: (1990) prescribed the best method that was used in the laboratory and was conducted for river sand, IOT and coarse aggregate.

3.2.3 Bulk density test on aggregates

Bulk density is the mass of material in a given volume. It is used in converting quantities by mass to quantities by volume and it is affected by several factors which include the amount of moisture present plus the amount of effort introduced in filling the measures. Bulk density depends on how densely the aggregate is packed and consequently on the size distribution and the shape of particles. BS 812 part 2: (1995) recognises two degrees: loose and compacted. The test was carried out as compacted and un-compacted on river sand, IOT and coarse aggregate samples.

3.2.4 Specific gravity test

Specific gravity is the ratio of the mass of a unit volume of material to the mass of the same (absolute) volume of water at the stated temperature. This depends on the volume of voids and the specific gravity of the materials of which it is composed. Two trial tests were carried out to ascertain the specific gravity of river sand, IOT and coarse aggregate. The test was in conformity to BS 812: part 2 (1995).

3.2.5 Aggregate impact value (AIV)

Aggregate Impact Value (AIV) is a determining measure of resistance to sudden impact or shock which is called toughness which may be completely different from aggregate crushing value. The test was carried out on the coarse aggregate only with the AIV apparatus in Appendix D1. The test was in conformity to BS 812: part 2 (1995).

3.2.6 Aggregate crushing value (ACV)

This test measures how resistance an aggregate is when being crushed while undergoing continuous applied load The test was carried out on coarse aggregate only. The test was in conformity to BS 812: part 2 (1995) while using the crushing mould and compression machine.

3.2.7 Mix design of concrete

Mix design was carried out to select the most suitable quantity of materials combination of IOT, sand, coarse, cement and water that will produce 90 cubes of concrete with 150 mm x 150 mm x 150 mm dimensions at a curing age of 3, 7, 14, 21 and 28 days respectively. The British method for the design of normal weight concrete made with Portland cement produced by Teychenné *et al.* (1997) was adopted for the concrete mix design.

The water–cement ratio is the most influential factor that affects strength. Hence the design charts and tables developed for mix proportioning are geared towards obtaining the minimum water–cement ratio that would produce a workable concrete. The maximum size of aggregate used for the experimental work was 20 mm. The control sample for the normal weight concrete mix design is required to satisfy the following requirements;

28 days cube characteristics compressive strength	F_c=25 N/mm^2
Assumed Slump	50 mm
Crushed aggregate with maximum size of	20 mm
Specific gravity of aggregate	2.74
The percentage defective permitted 5 %	k=1.64
Standard deviation	s = 8 N/mm^2
Margin, M	M= k x s = 1.64 x 8 = 13.12 N/mm^2
Type of cement used	OLC (strength class of cement =42.5)
Target mean strength	F_m = F_c + M = 25+13.12 = 38.12 N/mm^2

Step 1: Selection of target water/cement ratio

For cement strength class of 42.5 and using crushed aggregate, the 28-day compressive strength was found to be 49 N/mm^2. The water/cement ratio of 0.58 was arrived through the use of charts, tables and graphs (Teychenné *et al.*, 1997).

Step 2: Selection of free-water content

For 20 mm crushed aggregate and a slump of 50 mm, the water requirement is given as 210 kg/m^3. Source: (Teychenné *et al.*, 1997).

Step 3: Determination of cement content the cement content

$$\text{Cement content} = \frac{free-water\ content}{water-cement\ ratio} \tag{3.1}$$

The Cement content = 210/0.58 = 362.06 Kg/m^3

Step 4: Determination of total aggregate content

for water content of 210 kg/m^3 and specific gravity of aggregate of 2.74, (saturated surface-dry basis), the fresh density of concrete was found to be 2,430 kg/m^3. Hence, the total aggregate content is: 2430 – 362.06 – 210 = 1857.94 kg/m^3

Step 5: Selection of fine and coarse aggregate contents

for the maximum size of aggregate of 20 mm, percentage passing 600 µm sieve as 53 %, water-cement ratio 0.58 and a slump value of 50 mm, the proportion of fines was 36 %

the fine aggregate content as:

0.36 × 1857.94=668.88 kg/m^3.

Thus, the coarse aggregate content is 1857.94–668.88= 1189.12 kg/m^3. The mix design summary of the quantity of materials used to produce 1 m^3 of normal weight concrete in Table 3.1.

The concrete mix was prepared by carefully weighing and calculating the coarse aggregate, sand, IIOT, cement, and water with various replacement levels of sand by IIOT tested at 0, 5, 10, 15 and 20 % respectively in Table 3.2. For each replacement level 15 cubes were cast for compressive strength test and 15 cubes for the strain test at 28 days only as shown in Table 3.3.

Table 3.1: Materials requirement to produce 1 m^3 of normal weight concrete

Materials	Cement	Fine Aggregate	Coarse Aggregate	Water
Quantity (kg/m^3)	362.06	668.88	1189.12	210.0
Ratio	1.00	1.85	3.28	0.58
1 Bag of Cement (kg)	50.0	92.5	164.0	29.0

Table 3.2: Constituent materials of for 1 m^3 of concrete with IIOT

% replacement	Water (Kg/m^3)	Cement (Kg/m^3)	Fine Aggregate (Kg/m^3)	Itakpe Iron Ore Tailings (Kg/m^3)	Coarse Aggregate (Kg/m^3)
0 % IOT	210	362.06	668.88	0.00	1189.12
5 % IOT	210	362.06	635.44	33.44	1189.12
10 % IOT	210	362.06	601.99	66.89	1189.12
15 % IOT	210	362.06	568.55	100.33	1189.12
20 % IOT	210	362.06	535.10	133.78	1189.12

Table 3.3: Constituent materials of for 90 cubes (0.30375 m^3) of concrete

Concrete Samples	Water (kg)	Cement (kg)	Fine Aggregate (kg)	Itakpe Iron Ore Tailings (kg)	Coarse Aggregate (kg)
0 % IOT	63.79	109.98	203.17	0.00	361.20
5 % IOT	63.79	109.98	193.01	10.16	361.20
10 % IOT	63.79	109.98	182.86	20.32	361.20
15 % IOT	63.79	109.98	172.70	30.48	361.20
20 % IOT	63.79	109.98	162.54	40.63	361.20
Total	318.94	549.88	914.28	101.59	1805.98

3.2.8 Tests on fresh and hardened concrete

3.2.8.1 Slump test

The slump test was carried out in accordance with BS 1881: 108 (1983) using apparatus which consist of slump cone, tamping rod and steel rule in Appendix D2. The test was carried out on the fresh concrete mix containing the various batches of concrete mix at 0, 5, 10, 15 and 20 % respectively. The concrete mix design was implemented using the weight method of batching. Initially, the required quantities of sand and IIOT for the respective percentage replacements of IIOT with sand were weighed. Subsequently, water was measured based on the specified water-cement ratio. Additionally, the required amounts of cement and coarse aggregate were measured. These constituents were thoroughly mixed to form a uniform and workable paste. The slump test was conducted using a standard truncated slump cone with a bottom diameter of 200 mm, top diameter of 100 mm, and height of 300 mm. Concrete mix was compacted into the cone in three layers using a 600 mm long and 16 mm diameter tamping rod. After gently removing the cone, it was placed upside down beside the concrete, and the slump was measured using a meter rule. This process was repeated for two consecutive trials.

3.2.8.2 Compressive strength of the concrete

Compressive strength tests were conducted at the Department of Civil Engineering, Structural laboratory, Kaduna Polytechnic Tudunwada, Kaduna State. The hardened concrete samples for both control mixes and those with cement partially replaced with IOT and their respective density (unit weight) computed using the concrete cubes samples.

Three specimen cubes of 150mm x 150mm x 150mm were cast and tested after 3, 7, 14, 21 and 28 days of curing. The compressive strength was measured by subjecting the prepared concrete cube sample into the compressing strength machine in Plate III.

Compressive strength of concrete is the measurement of its resistance to crushing load applied directly; this implies the maximum compressive load the concrete can carry per unit area. The test was in conformity to BS 1881, Part 116 (1983).

Plate III: Compression testing machine

3.2.9 Strain test

Strain is the change in length per original length due to applied stress. Strains in concrete are the reduction in volume of concrete after the application of axial load which results to change in volume with respect to volume of concrete before applied load. Concrete as a brittle material shows or experiences small values of strains before failure and the elasticity and plasticity of a material depends on the stiffness, brittleness and ductility of the material which in turn lead to materials with higher strength and stiffness will lead to smaller strains and elastic regions. Strain is also the level a material stretches or compresses per unit of length when stress is applied. The strain test was in conformity to BS 1881: part 121 (1983) as conducted and summarised in Appendix C1.

Secant modulus of elasticity of concrete is the slope of between two points on the Stress-strain curve (SSC) and is usually applicable when the concrete specimen shows nonlinearity. The secant modulus can be determined between two points on the SSC by drawing a straight line from the origin to any desired stress point on the curve which is mostly 20 % to 85 % of the maximum compressive stress of the concrete specimen.

The concrete cube specimen was removed from the curing tank after 28 days curing age and air dried then, weighed on the weighing balance, the concrete cube specimen was carefully placed in the Mechanical strain gauge apparatus in Plate IV, then the dial gauge is zeroed and then placed in the compression testing machine. Readings on the mechanical strain dial gauge in Plate IV was recorded as the load was carefully applied at 100 kN intervals till failure on the concrete cube sample. The procedure was repeated tree times for accuracy and efficiency of results.

The mechanical strain gauge apparatus has a dial gauge with a calibration factor of 0.01mm. It is designed to measure concrete cubes of 150 mm x 150 mm x 150 mm in dimension as seen in Plate IV.

Plate IV: Mechanical strain gauge apparatus

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Materials Testing Results

This chapter provides a summary of the laboratory test results obtained from the samples, as detailed in the preceding chapter previous chapter. It also provides detailed interpretations of the resulting data.

4.1.1 Particle size distribution of aggregates

Appendix A1 and Appendix A2 show the result for the particle size distribution of sand and IIOT as fine aggregate. Figure 4.1 revealed that the sand and IIOT can be found within the category of zone 1 as stipulated in (BS 882, 1983). This means that their gradings are more coarse, higher percentage of the fine aggregate particles are larger in size, relatively lower surface area due to the coarser particles. This characteristic can influence the workability and water demand of concrete mixes. Aggregates in Zone 1 typically, have a higher void content, which can affect the overall density and strength properties of the concrete. However, this also provides improved workability.

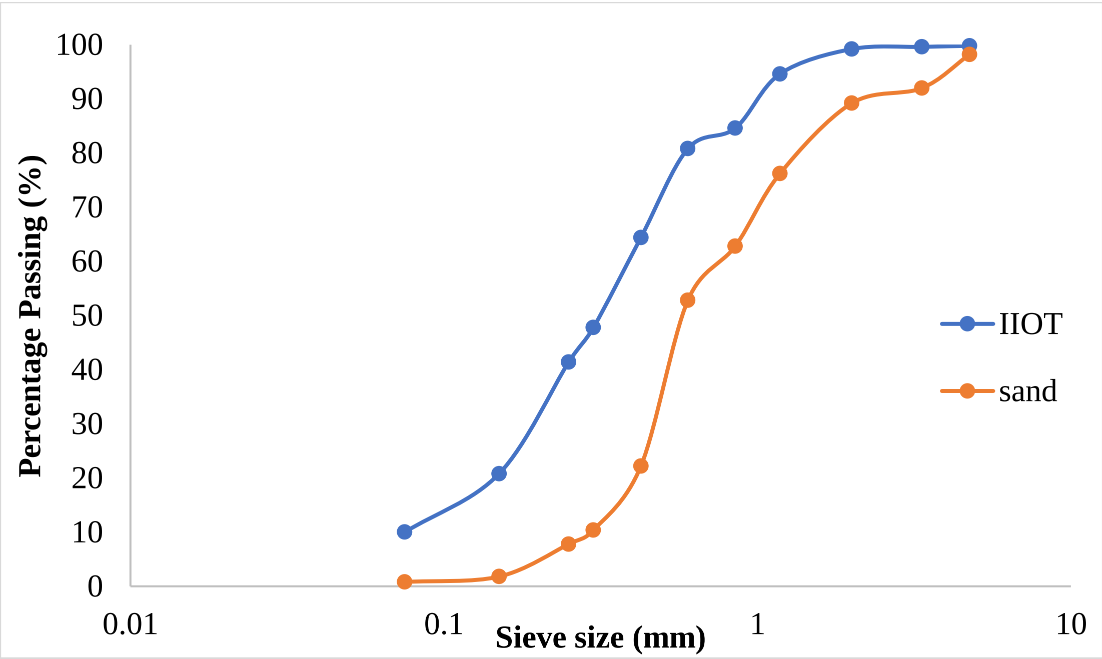

Figure 4.1: Particle size distribution of sand and IIOT

From Figure 4.2, revealed that the coarse aggregate can be found within zone 4 as stipulated in (BS 882, 1983). This means that the grading is more fine, higher percentage of the coarse aggregate particles are smaller in size, relatively higher surface area due to the finer and flaky and elongated nature of the aggregates as summarised in Appendix A3. This characteristic can influence the workability and water demand of concrete mixes. Coarse aggregates in Zone 4 typically, have a lower void content, which can lead to denser concrete mixes and strength properties of the concrete. However, this might also affect workability, requiring adjustments in the mix design to maintain the desired properties.

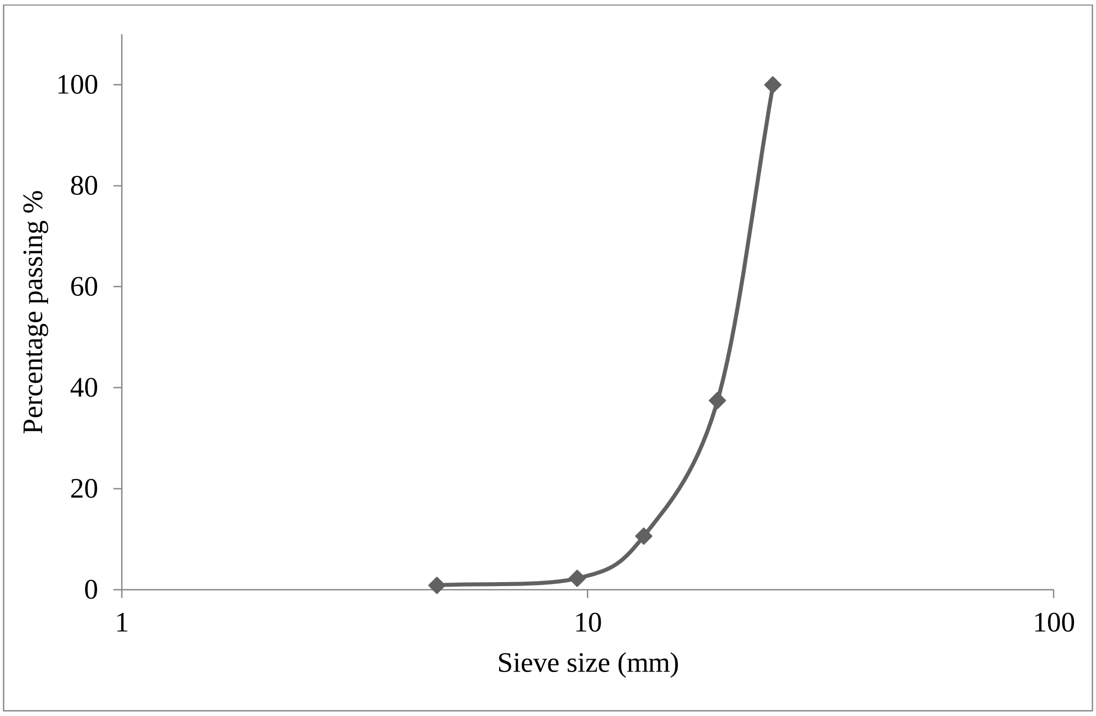

Figure 4.2: Particle size distribution of coarse aggregate

4.1.2 Natural moisture content

The average moisture content of sand obtained from Table 4.1 is 2.41 %. The moisture content of a soil depends on the void ratio of the soil thus, this value is indicative of the void spaces present in the soil. From Table 4.1 the moisture content obtained for IIOT is 5.74 % which is very close to that of coarse aggregate which is 6.94 this indicates that the

IIOT and coarse aggregates have high moisture than the sand. The computation where in guidance from BS 812: Part 109, 1990. Coarse aggregate moisture content was 6.97 % from Table 4.1.

It should be noted that the natural moisture content of soils is also dependent on the prevailing climatic conditions such as temperature, rainfall quantity. The water table level at the study area where the samples have been retrieved. (BS 812: Part 109, 1990).

Table 4.1: Moisture content of aggregates

Aggregates	Mean moisture content (%)
River sand	2.41
Itakpe iron ore tailings	5.74
Coarse aggregate	6.97

4.1.3 Bulk density test on aggregates

The average bulk density of sand was found to be 1537.44 kg/m^3 and 1688.68 kg/m^3 for un-compacted and compacted respectively, as shown in Table 4.2, these falls within the standard range of 1300-1800 kg/m^3 in accordance with (BS 812: Part 109, 1990). These implies that the aggregate is well-packed and densely composed.

The average bulk density of IIOT aggregate was found to be 1660.06 kg/m^3 and 1924.53 kg/m^3 for un-compacted and compacted respectively, as shown in Table 4.2, these are close to the standard range of 1300-1800 kg/m^3 in accordance to (BS 812: Part 109, 1990). These implies that the aggregate is more dense and heavier than sand due to the Iron (Fe) content in the IIOT, this is an indication that IIOT is a heavy weight aggregate and is heavier than most natural aggregate.

The average bulk density of coarse aggregate was found to be 1641.18 kg/m^3 and 1783.02 kg/m^3 for un-compacted and compacted respectively, as shown in Table 4.2, these falls within the standard range of 1300-1800 kg/m^3 in accordance to (BS 812: Part 109, 1990). These implies that the aggregate is well-packed and densely composed.

Table 4.2: Average bulk density of aggregates

Aggregates	Un-compacted (kg/m^3)	Compacted (kg/m^3)
River sand	1537.44	1688.68
Itakpe iron ore tailings	1660.06	1924.53
Coarse aggregate	1641.18	1783.02

4.1.4 Specific gravity test

The specific gravity of sand, IIOT and coarse aggregate were found to be 2.65, 3.12 and 2.74 respectively as indicated in Table 4.3. The value obtained for sand coarse aggregate falls within the limit for natural aggregates with value of specific gravity between 2.6 and 2.7 as reported in (Neville, 2000).

Table 4.3: Specific gravity of aggregates

Aggregates	Average specific gravity
River sand	2.65
Itakpe iron ore tailings	3.12
Coarse aggregate	2.74

4.1.5 Aggregate impact value (AIV)

The test was carried out on coarse aggregate samples, as shown in Appendix A13, the average of the two tests indicated 7.97 % for AIV, the aggregate is very strong and can withstand high impact loading and high concrete grade. Furthermore, this shows that the aggregate is very tough. The test was in conformity to BS 4550, Part 3, (1978).

4.1.6 Aggregate crushing value (ACV)

The test was carried out on the coarse aggregate samples, as shown in Appendix A14, the average of the two tests carried indicated 7.10 % for ACV, the aggregate is very strong and can withstand heavy continuous (uniform) loading and high concrete grade. The test was in conformity to BS 4550, Part 3, (1978).

4.1.7 Tests on fresh concrete

The values of the slump which is used to measure the fluidity, softness or wetness of a batch of concrete. The gradual decrease in slump height with increase in IIOT replacement is represented in the Figure 4.3.

The workability of the fresh concrete mixes experiences a significant reduction with the partial replacement of fine aggregate as the percentage of IIOT increases. The control mix had a slump of 45 mm while 5, 10, 15 and 20 % of the IIOT have slump of 40, 35, 30 and 25 mm respectively, which were in accordance with BS 1881: part 108 (1983).

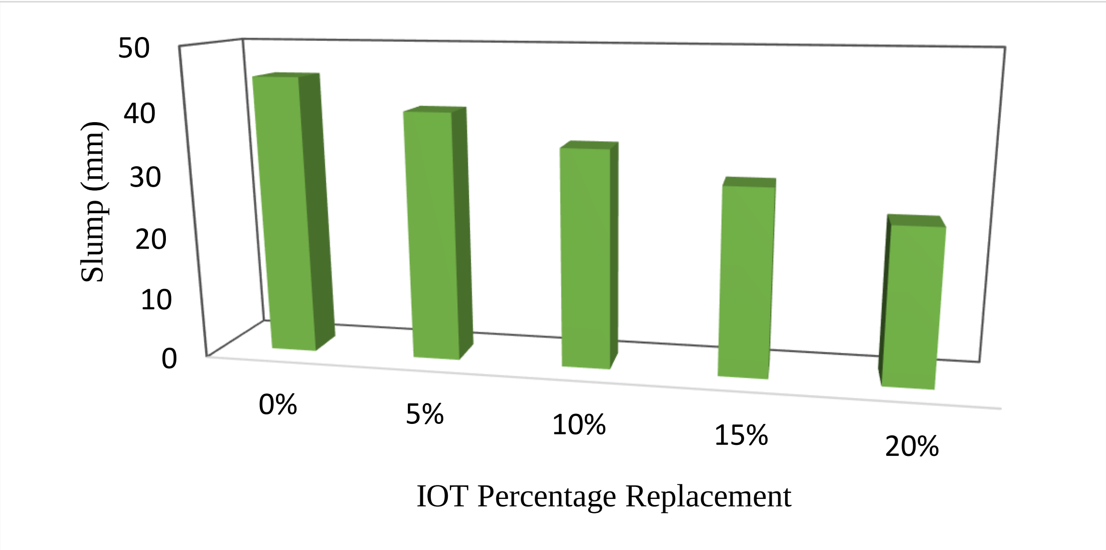

Figure 4.3: Slump of fresh concrete for various batches with percentages of IIOT

4.1.8 Test on hardened concrete

a) Compressive strength test

The compressive strength development at various ages is given in Appendix B and Figure 4.4. The compressive strength generally increased with curing age and increased with increased content of Itakpe Iron Ore Tailings (IIOT). The summary of results at 3 days as in Appendix B1 show that in all the replacement levels the percentage attainment of the design strength range between 62.40 % and 92.68 % with 0 % (control) IIOT content having 62.40 % and 5 % IIOT having the highest value of 92.68 %.

At 7 days as summarised in Appendix B2, the compressive strength of the control mix is 21.82 N/mm^2, representing 87.28 % of the design strength, while 20 % IIOT which had the highest 97.04 % of the design strength; while 5, 10 and 15 % IIOT replacement had compressive strength of 22.40, 23.54 and 21.89 N/mm^2 which is also 89.60, 94.16 and 87.56 % of the design strength respectively. These values satisfied the requirement of normal-weight concrete strength development as stipulated in BS 8110: part 2 (1985).

The strength development at 14 days as in Appendix B3 satisfied the 60-75 % of the design strength as stipulated (Preene, 2001). The compressive strength of the control mix is 22.16 N/mm^2, representing 88.64 % of the design strength, closely followed by 15 % IIOT which had 88.68 % of the design strength but 20 % IIOT had the highest at 26.11 N/mm^2 which was 104.44 % of the design strength while, 5 % and 10 % IIOT replacement had compressive strength of 25.17 N/mm^2 and 23.79 N/mm^2 which is also 100.68 % and 95.16 % of the design strength respectively.

At 21 days as summarised in Appendix B4, the compressive strength of the control mix was 23.31 N/mm^2, representing 93.24 % of the design strength. While 20 % IIOT was 28 N/mm^2 had the highest at 112 % of the design strength. 5, 10 and 15 % IIOT replacement had compressive strength of 26.88, 25.49 and 26.08 N/mm^2 which is also 107.52, 101.96 and 104.32 % of the design strength respectively.

The compressive strength of all sand replacement, 0, 5, 10, 15 and 20 % at 28 days hydration period as in Appendix B5 were 25.96, 30.47, 28.63, 30.45 and 30.20 N/mm^2 respectively which met the desired design strength of 25 N/mm^2.These are comparable with the values obtained by other researchers (Oritola *et al.*, 2015; Kuranchie *et al.*, 2015; Krikar and Hawkar, 2018). The strength development for IIOT percentage mix is faster up to 28 days hydration period whereas the control mix containing 0 % IIOT is lower. Thus, in case concrete needs to reach the maximum compressive strength in the shortest time, 20 % IIOT can be recommended for use in the concrete.

The increase in compressive strength for the replacement is due to presence and reasonable percentage of Iron (Fe) in tailings also, the increase can be due to the high density of the IIOT resulting to high strength concrete. The 20 % IIOT replacement can be categorised as the optimum due to the steady consistency in the increase of concrete throughout the curing days as shown in Appendix B. The rise in f_{cu} can be attributed primarily to the fine particles in IOTs, optimizing the pores within the structure. Moreover, the rough surface of IOTs, compared to that of sand, is a significant factor that cannot be overlooked.

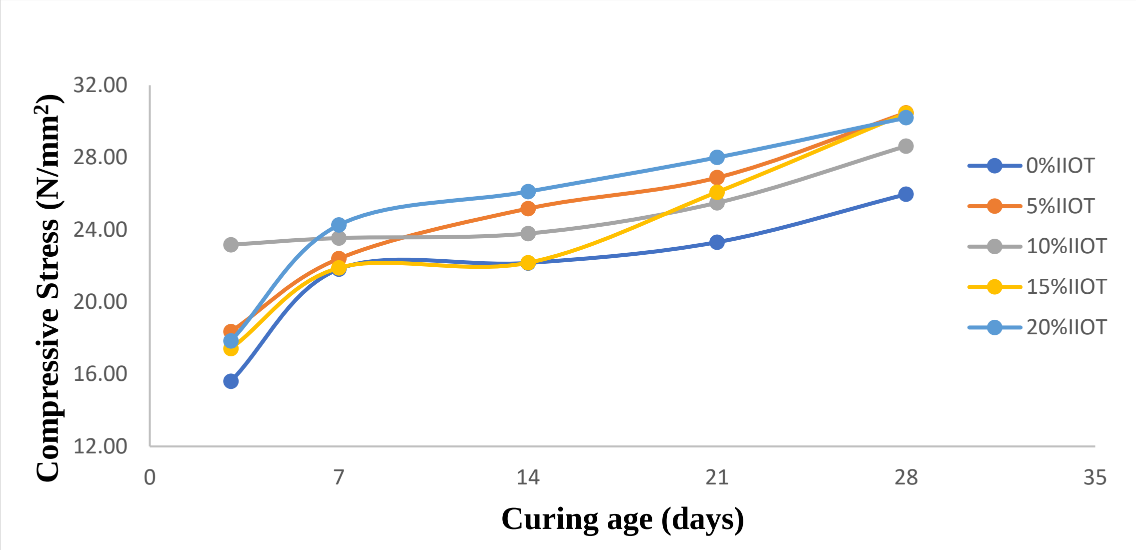

Figure 4.4: Compressive strength for various percentages of IIOT

b) Density of concrete

The density of the concrete increase as both the curing age and IIOT replacement increased which indicates that the IIOT concrete gave a more-dense concrete compared to the control. The control (0 % IIOT) had average densities of 2,187.65, 2,261.73, 2,281.48, 2,370.37 and 2,400.00 kg/m^3 at 3, 7, 14, 21 and 28 days respectively similarly, 5 % IIOT gave 2,350.62, 2,400.00, 2,419.75, 2,439.51 and 2,449.38 kg/m^3 for respective curing ages. Also, the resulting average densities for the respective ages of curing for 10 % IIOT were 2,281.48, 2,306.17, 2,439.51, 2,454.32 and 2,553.09 kg/m^3 while that of 15 % IIOT were 2,380.25, 2,400.00, 2,439.51, 2,469.14 and 2,500.74 kg/m^3 and finally, 20 % were 2,395.06, 2,479.01, 2,503.70, 2,523.46 and 2,543.21 kg/m^3. The density of the IIOT concrete is illustrated in Figure 4.5.

The density of the produced concrete cubes samples falls within the range 2,400 kg/m^3 to 2,553.09 kg/m^3 at 28 days which makes IIOT a heavy aggregate. The densities followed a steady increase in similar pattern with control were 2,553.09 kg/m^3 of 10

% IIOT was the highest. The increase in densities of IIOT concrete was due to the high Iron (Fe) content.

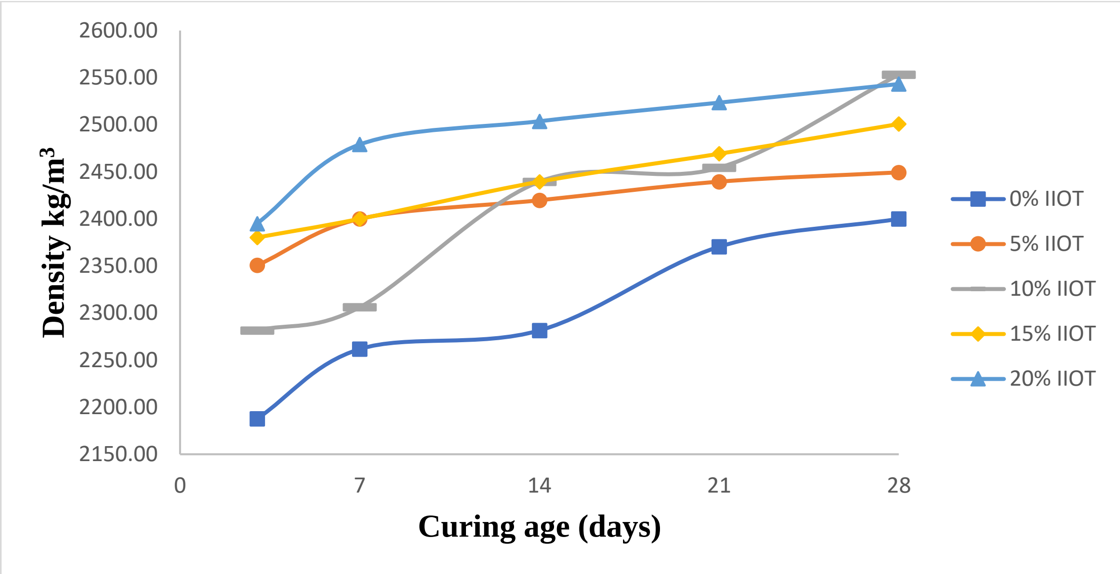

Figure 4.5: Density of concrete with various percentages of IIOT

c) Stress-strain of hardened concrete

The static modulus of elasticity, E_c, is determined directly from the stress–strain curve in Figure 4.6. In this study, the secant modulus was estimated and taken as the static modulus of elasticity of the concrete as stipulated in BS 8110 part 2 (1985). The secant modulus is generally evaluated as the slope of a line drawn from the origin to a point on the stress-strain curve corresponding to a stress 35–45 % of the maximum stress as expressed in Equation 4.1. In this study, a stress of 40 % of the maximum stress was used (Mehta and Monteiro, 2014).

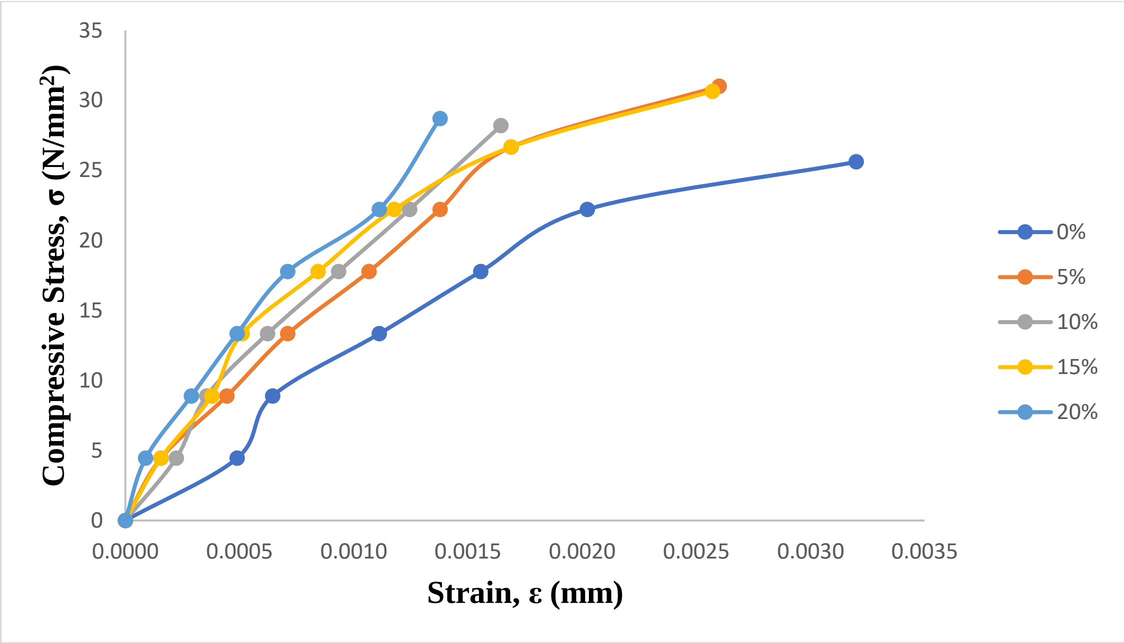

Figure 4.6: Stress-strain curves of various IIOT concrete at 28 days

Secant Modulus of Elasticity E, can be calculated with the expression,

$$E_c = \frac{Stress}{Strain} = \frac{\Delta y}{\Delta x} = \frac{y2-y1}{x2-x1} \qquad (4.1)$$

Where E_c = Secant Modulus of elasticity of Concrete

$\frac{\Delta y}{\Delta x} = slope$

y2 = 40% of the maximum axial compressive stress

y1 = minimum compressive stress, taken as the origin

x2 = corresponding Strain value on the x-axis from the value of *y2*

x1 = minimum axial strain, taken as the origin

The results of the static modulus of elasticity E_c, are presented in Table 4.4 at 28 days, the values are 13,666.67 N/mm^2, 19,076.92 N/mm^2, 23,500.00 N/mm^2, 25,541.67 N/mm^2 and 28,700.00 N/mm^2 for 0, 5, 10, 15 and 20 % IIOT replacement of sand respectively. At 28 days, the elasticity of concrete containing different percentages of IIOT was noted to increase at a faster rate than the control. For instance, the values increased at 39.59 %, 71.95 %, 86.89 %, and 110.00 % of the control mix for 5, 10, 15 and 20 % IIOT content respectively, which implies greater stiffness and rigidity in the IIOT concrete in turn tend to be more structurally stable, making it suitable for applications where stability and minimal deformation are critical, such as in high-rise buildings and bridges. All the mixes at 28 days where close to the range of concrete grade 25 at 28 days 19,000 N/mm^2 to 31,000 N/mm^2 stipulated by BS 8110 part 2 (1985).

Table 4.4: Secant modulus of elasticity of concrete

Slope determination	0% IIOT	5 % IIOT	10 % IIOT	15 % IIOT	20 % IIOT
Y2	10.25	12.40	11.28	12.26	11.48
X2	0.00075	0.00065	0.00048	0.00048	0.0004
Y1	0	0	0	0	0
X1	0	0	0	0	0
Static Modulus of elasticity, E_c (N/mm^2)	13,7000	19,100	23,500	25,540	28,700

In according to BS 8110 part 2 (1985) the equation for secant modulus of elasticity for normal-weight concrete is stated in Equation 4.2 while Umoh and Olusola (2012) stated the secant modulus of elasticity can be expressed as in Equation 4.3.

$$E_{c,28} = k + 0.2f_{cu,28} \qquad (4.2)$$

Where, $E_{c,28}$ is the static modulus of elasticity at 28 days

k is a constant closely related to the modulus of elasticity of the aggregate (taken as 20 kN/mm^2 for normal-weight-concrete)

$f_{cu,28}$ is the characteristic cube strength at 28 days (in N/mm^2)

$$E_{c,28} = 9.1\left(f_{cu,28}\right)^{0.33} \qquad (4.3)$$

Where, $E_{c,28}$ is secant modulus of elasticity at 28 days

$f_{cu,28}$ is characteristic cube strength at 28 days (in N/mm^2).

Concrete with a higher modulus of elasticity experiences less deformation under load, ensuring that the structure maintains its shape and form over time. This is essential for structures where deformation needs to be minimized, such as in precision engineering projects. The IIOT concrete would distribute loads more efficiently, reducing stress concentrations in specific areas. This property is valuable in large-scale constructions where even load distribution is crucial for the structural integrity of the building. Utilizing concrete with an increased modulus of elasticity allows for the design of thinner structural elements while maintaining the required strength and stability. This can result in material savings and more efficient use of resources.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the research carried out to achieve the set objectives, within the outlined scope. The followings were the conclusions drawn from the outcome of the research:

The specific gravity, uncompacted bulk density, compacted bulk density, moisture content for IIOT were found to be 3.12, 1660.06 kg/m^3, 1924.53 kg/m^3 and 5.74 % respectively. This indicates that the IIOT is a very dense tightly packed, coarsely grained and strong material to be used as fine aggregate replacement.

The slump decreases as the IIOT content increases. This means that the concrete becomes less workable (stiff) with increase in IIOT content; hence there is high demand for water to maintain the same workability level as the control. The compressive strength of IIOT concrete is much higher than the control and there is a continuous strength development with increase in IIOT replacement. The 20 % IIOT concrete attained strength of 120.8% above of the design strength at 28 days.

The stress-strain curves (SSC) for concretes with IIOT and river sand as fine aggregate showed similar behaviour. The SSCs for concrete with IIOT showed lower maximum strains, with a minimum of 23.08% lower than those of conventional concrete. Based on the characteristics of the SSCs, it can be concluded that the structural design process of concrete with IIOT within the elastic and inelastic range can be carried out normally without the need for modifications. The modulus of elasticity of concrete with IIOT was higher than concrete with river sand only. However, concrete with 20% sand replacement gave the highest (110.00% higher than concrete with no sand replacement) modulus of elastic of concrete.

5.2 Recommendations

Based on the outcome of the research, the followings are recommended:

a. From the outcome of the study 20% IIOT replacement for sand in concrete production was still the highest. Further study on replacement of IIOT above 20 % is recommended.
b. The IIOT concrete should be used where the high density of concrete does not affect the structure such as in road pavements.
c. IIOT concrete is recommended for works with high yield target strength concrete with readily available material waste materials within the locality.

5.3 Contributions to Knowledge

This study explores the potential of utilizing Itakpe Iron Ore Tailings (IIOT) as a sustainable alternative to Natural sand in concrete. Despite extensive research on concrete properties, there is a significant research gap in understanding the stress-strain characteristics of concrete with IIOT.

This is essential due to the lack of prior research and the potential for optimizing material usage. The research reveals that replacing 20% of sand with IIOT results in a 15% increase in concrete strength at 28 days, leading to stronger and more versatile concrete.

The elastic modulus improves significantly, increasing from 13,700N/mm^2 at 0% IIOT to 28,700N/mm^2 at 20% IIOT replacement. This innovative approach promotes sustainability by reducing reliance on sand and repurposing waste resources, with broad applications in various construction projects.

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APPENDICES

Appendix A: Physical Properties of concrete Constituents

Appendix A1: Sieve Analysis for Fine Aggregates – Total Sample Weight 1000g

Sieve size(mm)	Mass retained (g)	Cumulative weight retained (g)	Cumulative percentage retained (%)	Cumulative percentage passing (%)
4.75	18	18	1.8	98.2
3.35	62	80	8	92
2	28	108	10.8	89.2
1.18	130	238	23.8	76.2
0.85	134	372	37.2	62.8
0.6	100	472	47.2	52.8
0.425	306	778	77.8	22.2
0.3	118	896	89.6	10.4
0.25	26	922	92.2	7.8
0.15	60	982	98.2	1.8
0.075	10	992	99.2	0.8
Pan	8	1000	100	0

Appendix A2: Sieve Analysis for Itakpe Iron Ore Tailings – Total Sample Weight 1000g

Sieve size (mm)	Mass retained (g)	Cumulative weight retained (g)	Cumulative percentage retained (%)	Cumulative percentage passing (%)
4.75	2	2	0.2	99.8
3.35	2	4	0.4	99.6
2	4	8	0.8	99.2
1.18	46	54	5.4	94.6
0.85	100	154	15.4	84.6
0.6	38	192	19.2	80.8
0.425	164	356	35.6	64.4
0.3	166	522	52.2	47.8
0.25	64	586	58.6	41.4
0.15	206	792	79.2	20.8
0.075	108	900	90	10
Pan	100	1000	100	0

Appendix A3: Sieve Analysis for Coarse Aggregates – Total Sample Weight 1000g

Sieve size (mm)	Weight Retained (g)	Cumulative weight retained (g)	Cumulative percentage retained (%)	Cumulative percentage passing (%)
20	0	0	0	100
19	625.3	625.3	62.53	37.47
13.2	268.2	893.5	89.35	10.65
9.5	84	977.5	97.75	2.25
4.75	13.71	991.21	99.121	0.879
Pan	8.79	1000	100	0

Appendix A4: Moisture content of river sand

No of trial	A	B	C
Weight of can W_1 (g)	8.1	8.2	7.7
Weight of can + wet sample W_2 (g)	61.6	59.6	60.2
Weight of can + dry sample W_3 (g)	60.4	58.4	58.9
W_2-W_3	1.2	1.2	1.3
W_3-W_1	52.3	50.2	51.2
M.C (%)	2.29	2.39	2.54
Mean M.C for river sand (%)		2.41	

Appendix A5: Moisture content of itakpe iron ore tailings

No of trial	A	B	C
Weight of can W_1 (g)	7.6	7.7	7.8
Weight of can + wet sample W_2 (g)	90.2	102.5	97.1
Weight of can + dry sample W_3 (g)	86	97.4	91.9
W_2-W_3	4.2	5.1	5.2
W_3-W_1	78.4	89.7	84.1
M.C	5.36	5.69	6.18
Mean M.C for IOT (%)		5.74	

Appendix A6: Moisture content of coarse aggregate

No of trial	A	B	C
Weight of can W_1 (g)	7.8	8.2	7.6
Weight of can + wet sample W_2 (g)	87.6	90.6	76.5
Weight of can + dry sample W_3 (g)	87.5	76.5	76.4
W_2-W_3	0.1	14.1	0.1
W_3-W_1	79.7	68.3	68.8
M.C	0.13	20.64	0.15
Mean M.C for coarse aggregate (%)		6.97	

Appendix A7: Bulk density river sand

Fine Aggregate	Un-compacted		Compacted	
Number of Trials	1	2	1	2
Weight of mould (W_1) kg	2.55	2.55	2.55	2.55
Weight of mould + sample (W_2) kg	6.5	6.75	6.95	7.1
Net weight $M_{net} = (W_2 – W_1)$ kg	3.95	4.2	4.4	4.55
Volume of mould m^3	0.00265	0.00265	0.00265	0.00265
$Bulk\ Density = \frac{M_{net}}{V} kg/m^3$	1489.97	1584.91	1660.38	1716.98
Average bulk density kg/m^3	1537.44		1688.68	

Appendix A8: Bulk density itakpe iron ore tailings

IIOT	Un-compacted		Compacted	
Number of Trials	1	2	1	2
Weight of mould (W_1) kg	2.55	2.55	2.55	2.55
Weight of mould + sample (W_2) kg	6.7	7.2	7.1	8.2
Net weight $M_{net} = (W_2 - W_1)$ kg	4.15	4.65	4.55	5.65
Volume of mould m^3	0.00265	0.00265	0.00265	0.00265
$Bulk\ Density = \frac{M_{net}}{V} kg/m^3$	1565.41	1754.72	1716.98	2132.08
Average bulk density kg/m^3	1660.06		1924.53	

Appendix A9: Bulk density for coarse aggregate

Coarse Aggregate	Un-compacted		Compacted	
Number of Trials	1	2	1	2
Weight of mould (W_1) kg	2.55	2.55	2.55	2.55
Weight of mould + sample (W_2) kg	6.95	6.85	7.2	7.35
Net weight $M_{net} = (W_2 - W_1)$ kg	4.4	4.3	4.65	4.8
Volume of mould m^3	0.00265	0.00265	0.00265	0.00265
$Bulk\ Density = \frac{M_{net}}{V} kg/m^3$	1659.71	1622.64	1754.72	1811.32
Average bulk density kg/m^3	1641.18		1783.02	

Appendix A10: Specific gravity for river sand

Gs for river sand	Trial A	Trial B
Weight of cylinder (W_1) g	367.7	368
Weight of cylinder + sample (W_2) g	566.7	588.5
Weight of cylinder + sample + water (W_3) g	890.1	922
Weight of cylinder + water (W_4) g	767.5	783.5
$Specific\ gravity = \frac{(w2-w1)}{(w4-w1)-(w3-w2)}$	2.60	2.69
Average specific gravity	2.65	

Appendix A11: Specific gravity for itakpe iron ore tailings

Gs for IIOT	Trial A	Trial B
Weight of cylinder (W_1) g	368	367.7
Weight of cylinder + sample (W_2) g	550.1	541.8
Weight of cylinder + sample + water (W_3) g	1676.1	1666.5
Weight of cylinder + water (W_4) g	1550.7	1549.8
specific gravity $=\frac{(w2-w1)}{(w4-w1)-(w3-w2)}$	3.21	3.03
Average specific gravity	3.12	

Appendix A12: Specific gravity for coarse aggregate

Gs for Coarse Aggregate	Trial A	Trial B
Weight of cylinder (W_1) g	367.7	367.7
Weight of cylinder + sample (W_2) g	582.2	459.7
Weight of cylinder + sample + water (W_3) g	1287.8	1599
Weight of cylinder + water (W_4) g	1149.9	1541.4
specific gravity $= \frac{(w2-w1)}{(w4-w1)-(w3-w2)}$	2.80	2.67
Average specific gravity	2.74	

Appendix A13: Aggregate impact value for coarse aggregate

Details	TEST A	TEST B
Weight of mould + aggregate (W_1) g	3700	3500
Weight of mould (W_2) g	2650	2650
Weight of aggregate (W_1-W_2) g	1050	850
Weight of passing sieve 2.36mm (W_3) g	50	95
$AIV\ (\%) = \frac{W_3}{W_1 - W_2} \times 100$	4.76	11.18
Average aggregate impact value (%)	7.97	

Appendix A14: Aggregate crushing value for coarse aggregate

Details	TEST A	TEST B
Weight of mould + aggregate (W_1) g	14300	14560
Weight of mould (W_2) g	10450	10450
Weight of aggregate (W_1-W_2) g	3850	4110
Weight of passing sieve 236mm (W_3) g	200	370
$ACV\ (\%) = \frac{W_3}{W_1 - W_2} \times 100$	5.19	9.00
Average aggregate crushing value (%)	7.10	

Appendix B: Compressive Strength of Concrete

Appendix B1: Compressive Strength of Concrete Cubes (N/mm^2) at 3 days curing period

Percentage Replacement (%)	Weight (kg)	Average Weight (kg)	Load (kN)	Average load (kN)	Density (kg/m^3)	Failure stress (N/mm^2)
	7.50		357.0		2222.22	
0	7.40	7.38	374.2	351.10	2192.59	15.60
	7.25		322.1		2148.15	
	8.25		425.8		2444.44	
5	8.00	8.10	455.2	413.17	2370.37	18.36
	8.05		358.5		2385.19	
	8.50		521.0		2518.52	
10	8.75	8.62	560.1	521.23	2592.59	23.17
	8.60		482.6		2548.15	
	7.90		380.0		2340.74	
15	8.20	8.05	408.3	392.03	2429.63	17.42
	8.05		387.8		2385.19	
	8.30		467.3		2459.26	
20	8.00	8.08	376.2	401.40	2370.37	17.84
	7.95		360.7		2355.56	

Appendix B2: Compressive Strength of Concrete Cubes (N/mm^2) at 7 days curing period

Percentage Replacement (%)	Weight (kg)	Average Weight (kg)	Load (kN)	Average load (kN)	Density (kg/m^3)	Failure stress (N/mm^2)
	7.75		481.5		2296.30	
0	8.00	7.63	492.8	490.87	2370.37	21.82
	7.15		498.3		2118.52	
	8.30		508.4		2459.26	
5	8.00	8.17	520.7	504.00	2370.37	22.40
	8.20		482.9		2429.63	
	7.85		512.4		2325.93	
10	7.75	7.83	548.2	529.67	2296.30	23.54
	7.90		528.4		2340.74	
	8.25		521.3		2444.44	
15	8.00	8.08	468.7	492.53	2370.37	21.89
	8.00		487.6		2370.37	
	8.40		572.1		2488.89	
20	8.85	8.52	548.0	545.77	2622.22	24.26
	8.3		517.2		2459.26	

Appendix B3: Compressive Strength of Concrete Cubes (N/mm^2) at 14 days curing period

Percentage Replacement (%)	Weight (kg)	Average Weight (kg)	Load (kN)	Average load (kN)	Density (kg/m^3)	Failure stress (N/mm^2)
	8.00		507.6		2370.37	
0	7.30	7.70	492.0	498.60	2162.96	22.16
	7.80		496.2		2311.11	
	8.10		579.8		2400.00	
5	7.80	7.93	610.8	566.27	2311.11	25.17
	7.90		508.2		2340.74	
	7.70		532.9		2281.48	
10	7.80	7.70	547.2	535.27	2311.11	23.79
	7.60		525.7		2251.85	
	8.00		545.0		2370.37	
15	8.20	8.10	495.4	498.77	2429.63	22.17
	8.10		455.9		2400.00	
	8.30		507.0		2459.26	
20	8.50	8.58	579.6	587.43	2518.52	26.11
	8.95		675.7		2651.85	

Appendix B4: Compressive Strength of Concrete Cubes (N/mm^2) at 21 days curing period

Percentage Replacement (%)	Weight (kg)	Average Weight (kg)	Load (kN)	Average load (kN)	Density (kg/m^3)	Failure stress (N/mm^2)
	8.10		546.9		2400.00	
0	7.90	8.00	498.7	524.47	2340.74	23.31
	8.00		527.8		2370.37	
	8.30		596.0		2459.26	
5	8.10	8.27	606.9	604.87	2400.00	26.88
	8.40		611.7		2488.89	
	8.00		556.9		2370.37	
10	8.20	8.23	590.1	573.50	2429.63	25.49
	8.50		613.6.1		2518.52	
	8.40		600.7		2488.89	
15	7.80	8.03	567.5	586.87	2311.11	26.08
	7.90		592.4		2340.74	
	8.50		649.1		2518.52	
20	8.20	8.37	628.3	630.10	2429.63	28.00
	8.40		612.9		2488.89	

Appendix B5: Compressive strength of concrete cubes (N/mm^2) at 28 days curing period

Percentage Replacement (%)	Weight (kg)	Average Weight (kg)	Load (kN)	Average load (kN)	Density (kg/m^3)	Failure stress (N/mm^2)
	7.15		553.9		2118.52	
	7.75		602.5		2296.30	
	8.00		572.0		2370.37	
0	8.65	8.00	589.9	584.07	2562.96	25.96
	8.50		591.8		2518.52	
	7.95		594.3		2355.56	
	8.30		675.3		2459.26	
	8.10		761.4		2400.00	
	7.10		701.7		2103.70	
5	7.80	7.95	656.5	685.65	2311.11	30.47
	8.08		680.8		2394.07	
	8.32		638.2		2465.19	
	7.40		606.1		2192.59	
	8.10		616.3		2400.00	
	7.85		615.8		2325.93	
10	8.70	8.20	680.7	644.12	2577.78	28.63
	8.48		660.8		2512.59	
	8.67		685.0		2568.89	
	8.00		714.0		2370.37	
	7.55		667.3		2237.04	
	7.85		656.7		2325.93	
15	8.00	7.96	687.8	685.18	2370.37	30.45
	7.98		678.6		2364.44	
	8.35		706.7		2474.07	
	8.10		685.4		2400.00	
	7.45		644.0		2207.41	
	8.25		672.9		2444.44	
20	7.95	8.24	661.7	679.48	2355.56	30.20
	8.9		708.4		2637.04	
	8.81		704.5		2610.37	

APPENDIX C: COMPRESSIVE STRAIN OF CONCRETE

Appendix C1: Compressive strain readings of concrete cubes at 28 days curing period

Strain Readings				Calibrating Factor = 0.01mm						
Percentage	Load (kN)	Average load (kN)	Stress (N/mm^2)	100kN	200kN	300kN	400kN	500kN	600kN	700kN
	553.9			0.0004	0.0005	0.0007	0.0011	0.0017	0.0000	
0	572.0	576.13	25.61	0.0005	0.0008	0.0015	0.0019	0.0026	0.0000	
	602.5			0.0006	0.0007	0.0011	0.0017	0.0018	0.0021	
	675.3			0.0000	0.0005	0.0007	0.0013	0.0015	0.0017	0.0000
5	761.4	697.73	31.01	0.0003	0.0005	0.0010	0.0013	0.0017	0.0020	0.0021
	656.5			0.0002	0.0003	0.0004	0.0007	0.0009	0.0013	0.0000
	606.1			0.0002	0.0003	0.0004	0.0005	0.0006	0.0010	0.0000
10	616.3	634.37	28.19	0.0001	0.0001	0.0005	0.0007	0.0010	0.0013	0.0000
	680.7			0.0004	0.0007	0.0010	0.0015	0.0021	0.0027	0.0000
	714.0			0.0000	0.0003	0.0006	0.0010	0.0016	0.0023	0.0024
15	667.3	689.70	30.65	0.0002	0.0003	0.0004	0.0007	0.0009	0.0013	0.0000
	687.8			0.0003	0.0005	0.0005	0.0008	0.0010	0.0014	0.0000
	648.5			0.0000	0.0002	0.0005	0.0007	0.0010	0.0016	0.0000
20	661.7	646.03	28.71	0.0001	0.0003	0.0006	0.0008	0.0010	0.0013	0.0000
	627.9			0.0001	0.0003	0.0004	0.0007	0.0013	0.0012	0.0000

APPENDIX D: PLATES

Appendix D1: Aggregate impact value apparatus

Appendix D2: Slump cone and 20% IIOT slump