DEVELOPMENT OF METAKAOLIN SELF-COMPACTING CONCRETE FOR HIGH AXLE MONOLITHIC RIGID PAVEMENT

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A THESIS SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING, COLLEGE OF ENGINEERING, COVENANT UNIVERSITY OTA, OGUN STATE, NIGERIA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY (Ph.D) DEGREE IN CIVIL ENGINEERING

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ACCEPTANCE

This is to attest that this thesis is accepted in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Civil Engineering in the Department of Civil Engineering, College of Engineering, Covenant University, Ota, Ogun State, Nigeria.

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DECLARATION

I, BUSARI Ayobami Adebola (14PCI00813), declare that this research was carried out by me under the supervision of Prof. Joseph AKINMUSURU of the Department of Civil and Environmental Engineering, Covenant University, Ota, Ogun State and Dr. Bamidele DAHUNSI of the Department of Civil and Environmental Engineering, University of Ibadan, Oyo State. I attest that the thesis has not been presented either wholly or partly for the award of any degree elsewhere. All sources of data and scholarly information used in this thesis are duly acknowledged.

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Signature & Date

CERTIFICATION

We certify that this thesis titled "Development of Metakaolin Self-Compacting Concrete for Pavement" is an original work carried out by BUSARI Ayobami Adebola (14PCI00813), in the Department of Civil Engineering, College of Engineering, Covenant University, Ota, Ogun State, Nigeria, under the supervision of Prof. AKINMUSURU Joseph and Dr. DAHUNSI Bamidele. We have examined and found the work acceptable for the award of a degree of Doctor of Philosophy in Civil Engineering (Highway and Transportation Engineering Option).

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DEDICATION

This research is dedicated to my parents and my husband for their sacrifice, love and constant support.

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TABLE OF CONTENT

CHAPTER THREE

MATERIALS AND METHODS

LIST OF TABLES

LIST PLATES

LIST OF FIGURES

LIST OF ACRONYMS

JPCP	Jointed plain concrete pavement
JRCP	Jointed reinforced concrete pavement
CRCP	Continuously reinforced concrete pavement
CBR	California Bearing Ratio
IP	Intersection Point
PC	Beginning of Circular Curve/Tangent point
PT	End of Circular Curve/ Tangent Point
T	Tangent Length
D	Deflection Angle
L	Length of Curve
E	External Distance
SCC	Self-Compacting Concrete
NC	Normal Concrete
BRT	Bus Rapid Transit
MKSCC	Metakaolin Self Compacting Concrete
MKSCC (A)	Metakaolin Self Compacting Concrete with Brand a Cement
MKSCC (B)	Metakaolin Self Compacting Concrete with Brand B Cement
RSM	Response Surface Analysis
ASTM	American Standard Testing Method
AASHTO	American Association of State Highway and Traffic Officials
XRF	X-ray fluorescence spectrometer
SEM	Scanning Electron Microscope

ABSTRACT

Defects of asphaltic concrete pavements in Nigeria due to the effect of high axle vehicle have become a stigma. Hence, the recent interest in rigid pavements as a sustainable solution. The high strength required for rigid pavements is often achieved by the use of additives and admixtures to concrete during production. In this study, the choice of metakaolin in self-compacting concrete for rigid pavement construction was assessed. This research was divided into three stages. The first stage involved the development of Metakaolin Self-Compacting Concrete (MKSCC) and Pigmented Metakaolin Self-Compacting Concrete (PMKSCC) using two brands of cement. The rheology and strength properties of twenty-four (24) concrete mixes were examined at 3, 7, 14, 21, 28, 56, 91, 121 and 150 days. Pavement application of the strength parameters was assessed using AASHTO specifications. The second stage involved the Mechanistic-Empirical design of a typical high axle road and the assessment of the stress-strain parameters using Finite Element Analysis. Numerical analysis of the strength parameters was done in the third stage using Response Surface Analysis. The result of the rheology showed that 10% addition of metakaolin showed satisfactory results. However, at higher percentages, the passing ability, flowing ability, and the segregating ability became unsatisfactory. The pavement application of the strength properties recorded showed that at 10% replacement, the flexural strength of 4.86 MPa was obtained. This strength value is higher than the required specification of 4.27 MPa for pavement construction at 28 days; it also satisfies the requirement for high axle and airfield pavement. In a bid to minimize cost, the use of MKSCC (B) in concrete pavement is appropriate, as the strength properties were satisfactory up to 20%. However, to optimize strength, the use of MKSCC (A) is appropriate as it showed the highest strength The Mechanistic-Empirical pavement design of a typical high axle section of Abaji road (Northern Nigeria) gave a thickness of 254 mm and 251.5 mm for the two MKSCC developed. This was used in establishing the stress-strain relationship using Finite Element Analysis. The result revealed that 6.5 % stress was reduced based on the modulus of elasticity of the MKSCC and the control. The displacement in the pavement was noticed at the symmetry line where the tandem wheel load was applied. Numerical analysis using response surface model revealed that at a low value of Metakaolin, a positive relationship exists between the strength parameters and age of concrete. From the numerical optimization obtained, the maximum predicted compressive and flexural strength of 44.35 N/mm^2 and 6.18 MPa is achievable under the optimum concrete formation of 110 days, a metakaolin content of 52.73 Kg and water/cement ratio of 0.4. The desirability of 1.00 was achieved with the numerical optimization performed, showing the best accuracy of the optimization process. Additionally, the R^2 value of 0.91 % was obtained from the model equation which established the robustness of the model. Ultimately, this research revealed that the choice of metakaolin in self-compacting concrete for rigid pavement construction reduced the construction cost and increased the strength of the pavement. Hence MKSCC is a strong, sustainable, and eco-friendly alternative in rigid pavement construction.

Keywords**:** Pavement, Sustainability, Metakaolin, Self-compacting Concrete, Pigments, Finite Element Analysis

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Transport is an indispensable element of development and socio-economic growth of a country. As the engine of economic integration, transport infrastructures constitute a precondition for facilitating trade and the movement of goods and person. Mabogunje, (2008) stated that all phases of public transportation in Nigeria, especially road transportation are today in varying degrees of degeneration due to pavement defects. Pavement failure has to do with the unsatisfactory performance of the pavement interlayers. Pavement interlayer defect due to high axle load is a major problem faced by highway engineers all over the world. The need for a strong and durable pavement to accommodate increased axle load and increased demand for transportation infrastructures due to population increase is necessary for efficient mobility.

Additionally, the demand for highway facilities, especially in cities of developing countries is increasing at a higher rate due to population increase. This population increase has exerted a huge constraint on the few available flexible pavements (Odeleye, 2008). Therefore, the need for the introduction of a mass transit scheme like Bus Rapid Transit (BRT) which is an example of high axle vehicle is paramount in major Central Business District (CBD) in Nigeria in a bid to accommodate this ever-increasing population. Consequently, the adequate design is required to accommodate tandem and tridem axle vehicles such as heavy trucks used for transportation of goods and raw materials in Nigeria.

The choice of flexible pavement for high axle vehicles may not be adequate because of its strength, and durability limitations. Therefore the selection of rigid pavement is important due to its unique attributes which include longer lifespan, reduced maintenance costs and higher strength among others. This necessitated its choice in this research. Nevertheless, despite these attributes, a huge capital investment is required for its construction and this to a very large extent has limited its usage.

In a bid to reduce construction cost of rigid pavements in developing countries, the need to reduce the quantity of cement is paramount. Cement is one of the most expensive components of concrete technology and as such, reducing concrete cost requires the reduction of cement quantity among other factors (Memphis, 2014). In a bid to reduce the cost of cement and improve on sustainability, the use of Supplementary Cementitious Material (SCM) in the form of metakaolin was utilized in self-compacting concrete in this research. This was selected based on its abundance in Nigeria. The need for sustainable material and the reduction of concrete cost led to the advent of SCM. SCM is a finely ground, solid material, used as a replacement for cement in concrete production. These materials react chemically with hydrating cement due to their pozzolanic properties to form a modified paste microstructure similar to silica fume, rice husk ash, fly ash, metakaolin etc. (Sanjay, Anil and Subhash, 2014).

In line with the campaign for sustainability in road construction, the use of metakaolin was seen as a viable option in this research. Metakaolin, which is a relatively new material in the concrete industry, is effective in increasing strength, improving durability, improving air-void network, reduction in shrinkage and improvement in water tightness of concrete (Sanjay *et al.*, 2014). This material was incorporated in Self-Compacting Concrete (SCC) in this study. SCC is a innovation and a breakthrough in the construction industry. It provides many new solutions to the fresh and hardened properties of concrete. This type of concrete is also referred to as self-consolidating concrete, self-leveling concrete and so on (Kurita and Nomura, 1998).

SCC is of great attraction today in the traditional construction industry. It has been adopted in the construction of bridges, tunnel, and structures; the successful development of SCC guarantees a right balance between deformability. The incorporation of metakaolin in SCC is required to improve the strength of the pavement in the design and construction of high axle pavement with an expected axle load of 2.5 Million Equivalent Standard Axle Load and above (AASHTO, 1993). Metakaolin induced concrete will make concrete affordable for road construction in developing and under-developed countries with an abundance of kaolin, a sustainable material.

There are indications that Public-Private Partnership arrangement between cement manufacturers and the government may be established, so the viability of concrete pavement is now considered a solution to the prevalent flexible pavement defect. Consequently, the need for sustainability and reduced labour cost of the construction of concrete road spurred the choice of metakaolin self-compacting concrete in this research.

1.2 Statement of Research Problem

Nigerian roads are the most important means of transportation in the country, carrying 90% of the people and goods. There is about 200,000 km of paved roads in the country, out of which 90% are asphaltic concrete roads (Oguara, 2006). Most of these roads are in various degrees of pavement deterioration such as raveling, cracks, potholes and disintegration among others which has led to the loss of structural strength of pavements. Traffic volume and size, primarily attributed to high axle loads (80 KN/mm^2 and above) also contribute to this problem. This condition is evidenced in Nigeria which is the largest and most populated country in Africa. In a bid to improve the strength of pavements in Nigeria, there is a need for government and relevant agencies to embrace the use of rigid pavement.

Additionally, highway agencies have reported service life of concrete pavements to be between 25–40 years, which is about (1.5 - 2) times the service life of asphaltic concrete pavements designed and built to similar standards (AASHTO, 1982). As a result, concrete is now generally selected especially for the construction of heavily trafficked and high axle pavements. Rigid pavements typically accommodate higher axle loads than the asphaltic concrete pavements due to the stress distribution pattern of concrete.

Nigeria is in recession and many contractors are on hold due to lack of funds and spike in the cost of construction materials. The high increase in the cost of cement has led to the reduction in road construction in most developing and under-developed countries. Therefore, the need for a sustainable and cost-effective substitute for cement is necessary.

In a bid to solve the cost problem (both material and labour costs), there is a need to look inward at the available raw materials and technology needed to make concrete affordable. This necessitated the choice of metakaolin and SCC. Kaolinitic clay is available globally (Sanjay *et al.,* 2014) and it is readily available in Nigeria (Ogundiran, and Ikotun, 2014). It has numerous advantages such as the enhancement of strength and durability among others.

Utilizing this material will help in the design of a stable and economical mix for the construction of the concrete road. Additionally, the incorporation of this material as a replacement for cement will also make rigid pavement construction affordable in developing and underdeveloped countries now and in the foreseeable future.

1.3 Aim

The aim of this research is to assess the properties of self-compacting concrete admixed with varying proportions of metakaolin and pigments for application in the design and construction of rigid pavement using two selected brands of Portland Limestone cement.

1.4 Objectives

The objectives of the research are to:

i. determine the workability and strength properties of SCC for pavement construction by incorporating metakaolin as a partial replacement for cement at 0, 5, 10, 15, 20 and 25%.
ii. examine the workability and mechanical properties of pigmented Metakaolin Self-Compacting Concrete for two cement brands at 0, 2, 4, 6, 8 and 10% pigment additions.
iii. design a typical rigid pavement using Mechanistic-Empirical approach and analyse the stress-strain distribution with Finite Element Analysis.
iv. generate models to relate the properties of the metakaolin self-compacting concrete to the strength parameters using response surface analysis of design expert model 10 X 10.

1.5 Justification for the Study

Early failure of flexible pavement before the expected design life under repetitive axle load and the huge amount incurred in the construction of rigid pavement necessitate the use of cheaper alternative materials. This is used to partially replace the constituents of concrete mixture used in rigid pavement construction.

Therefore, the construction of rigid pavement for high axle vehicles requires concrete with high strength, high performance, and structurally stable concrete such as self-compacting concrete. Utilization of SCC is of copious advantage over the normal concrete used in rigid pavement. To improve constructability, reduce labour costs, improve structural strength, improve the performance of the pavement and accelerate project schedule the use of self-compacting concrete was espoused. It is noteworthy that research on SCC in the past focused on the structural application. However, dearth of literature exists in the choice of SCC and metakaolin self-compacting concrete in road construction. Additionally, in a bid to reduce construction cost and improve the strength of pavement, the choice of metakaolin was espoused.

The success of this research will reduce the frequency of pavement failure as the incorporation of metakaolin will reduce the quantity of cement, increase the strength of pavement, and help in pavement crack control. The development of this special concrete will also provide database for government, ministries, engineering firms, road construction specialist, maintenance agencies, highway research institutes, and transportation planning agencies on the optimum quantity of metakaolin required for the two major brands of cement in the road construction industry. Moreover, it will be useful in improving the strength of concrete roads both locally and globally in track with the millennium development goal sub-theme 9 and 11.

1.6 Scope of Study

This study is limited to the use of Ekiti sourced metakaolin in southwestern Nigeria, because of its unique pozzolanic properties as ascertained by literature. Also, based on its specification as raw natural pozzolans for use as a mineral additive (ASTM C-618-12). The de-hydroxylation of the metakaolin at 750^0C was used all through the research. The research focused on a single de-hydroxylation temperature for consistency of the design matrix. Also, Nigerian bagged Portland limestone cement was adopted since Ordinary Portland Cement is not available in the country. Medium grade concrete was developed and used all through the research process. Additionally, the replacement of metakaolin was done at 5%, 10%, 15%, 20% and 25% of the dry weight of cement.

The strength parameters were interpreted for road construction using Nigerian General Specification (1997) and AASHTO, (1993). Additionally, the research focused on self-compacting concrete using vibrated concrete as the control. There seems to be a dearth of literature on the application of self-compacting concrete in road construction, which largely limited the research work. Also, the powdered pigment was used in the development of pigmented metakaolin Self-Compacting Concrete samples. Other types of pigments (liquid and gas) are expensive and hence may not be economically viable for pavement construction. The addition of the pigment did not exceed 10% based on ASTM guide.

Finite Element Analysis was limited to the assessment of the stress-strain relationship. Additionally, only Mechanistic-Empirical approach was adopted in the pavement thickness design in this research.

1.7 Structure of the Thesis

Chapter One

This chapter entails the background to the study and the statement of research problem were well stated. The aim and objectives were listed and the justification for the choice of metakaolin and SCC were also included with the definition of the acronyms used in the research. Relevant literature as regards rigid pavement design and construction are discussed in the next chapter.

Chapter Two

This section deals with the review of literature relevant to the research. To this end, literatures on previous research on the utilization of alternative cementitious materials used in concrete was espoused. Also, the various design approaches used in the design of rigid pavement were reviewed, including the choice of Finite Element Analysis. This was done with the aim of providing the basic principle guiding the design of self-compacting concrete mix and rigid pavement design. Gaps in the literature which formed the basis of this research were identified.

Chapter Three:

This chapter describes the methodological framework used in attaining the stated objectives and aim of this research. The information on research materials, mix design, fresh properties and hardened properties test were explained. The research design, procedures, and tests used in achieving the objectives were well stated. Also, the description of the methods used in data analysis and the formulation of the model parameters was discussed. The results of the procedure discussed in this section are explained in chapter four.

Chapter Four

The results of the experimental works were analyzed in this section. This was done with special focus on the objectives of the research. The design of a typical high axle pavement was done to show the suitability of the concrete developed for high axle pavement design and construction. Numerical optimization models were developed and discussed in this chapter as well. Design using the Mechanistic-Empirical method and Finite Element Analysis was done using relevant highway design code. The conclusion and recommendations for future work are discussed in the next chapter.

Chapter Five:

The conclusion of the whole thesis was presented in this chapter. Also, recommendations for future research and for professionals in the road construction industry were also stated.

1.8 Chapter Summary

Road transportation is essential in the development of any nation. There is a need for improved technology to make the design and construction of pavement, especially rigid pavement affordable in developing nations like Nigeria. Metakaolin is a naturally abundant mineral material in Nigeria and was adopted in achieving the aim of the research. The problem statement of frequent pavement defect and the need for a strong and durable pavement to accommodate high axle pavement were explained.

Ultimately, the goal of this research is to develop a metakaolin and pigmented metakaolin self-compacting concrete to reduce the cost of rigid pavement construction by reducing the quantity of cement which is one of the most expensive components of concrete production using kaolinitic clay.

In this section of the thesis, the objectives were stated in achieving the aim of the study. The next chapter focused on relevant literature about the development of metakaolin self-compacting concrete in rigid pavement construction.