UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT AND PERFORMANCE OF MODIFIED CLAY NANOPOROUS PIPE FOR SUBSURFACE IRRIGATION

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DEVELOPMENT AND PERFORMANCE OF MODIFIED CLAY NANOPOROUS PIPE FOR SUBSURFACE IRRIGATION

By

SALISU ABDULLAHI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2021

DEDICATION

I dedicate this work to my parents, family members, my institution Usmanu Danfodiyo University Sokoto (UDUS) and those that contributed to the success of the program. Your affection, understanding, patience, perseverance and support throughout the study period is highly appreciated.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT AND PERFORMANCE OF MODIFIED CLAY NANOPOROUS PIPE FOR SUBSURFACE IRRIGATION

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March 2021

Chairperson : Aimrun Wayayok, PhD
Faculty : Engineering

Clay pipes are continuously gaining prominence for irrigation water management in drier regions. However, information on soil wetting patterns is a key requirement for understanding subsurface irrigation system design and management, even though current approaches are mathematically complex. The aim of this study, therefore, is to develop porous clay pipes and evaluate their performance and use the pipes to evaluate the prospect of a newly proposed method of non-contact thermography for wetting pattern study under laboratory experimental conditions. To achieve this, clay soil from Rege pits and zeolite were used as raw materials for the production of pipes. American Society of Testing and Materials (ASTM) standard procedures were followed for soil physical properties, consistency and linear shrinkage tests. Chemical compositions of the samples, morphological characteristics of the samples and the produced pipes were analysed using Electron Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM). The geometry, specific surface area, pore-volume, pore diameter, hydraulic characteristics and absorption capacities of the produced pipes were evaluated using standard methods. Three different pipe types: rubber, clay and modified clay (clay mixed zeolite) porous pipes were used for soil wetting pattern study in the laboratory using Plexiglas soil column packed with homogeneous sandy soil. FLIR E60 infrared camera was used for wetting pattern images acquisition at different application times. Supervised Classification method of Maximum Likelihood Algorithm in ArcGIS 10.7.1 software interface was used to analyse the images. From the results, the soil was found to be clay with 11 % sand, 34 % silt and 55 % clay, particle density and bulk density as 2.43 and 1.58 g/cm^3 respectively. The addition of zeolite shows a decrease in both liquid limit, plastic limit and shrinkage of the clay from 50.7, 27.6 and 11.67 % to 43.7, 27.3 and 8.92 % respectively, with Plasticity Index (PI) from 11.67 to 8.92. The samples are aluminosilicate materials with silica and alumina as main constituents, and traces of iron, potassium and cobalt. The external and internal diameters of 12 clay pipes ranged from 3.7±0.05 cm and 2.1±0.05 cm, while 12 modified clay pipes are 3.7±0.12 and 2.3± 0.22 cm. The modified clay pipes recorded higher surface area, pore-volume, and pore diameters of 4.46±0.20, 0.001044±0.000054 and 6.29±0.42, respectively. Moreover, the modified pipes have a high absorption capacity to that of clay pipes. The pipes emission rates operated at 0.2 bar were 2.54, 2.26 and 2.84 L/h per meter length of rubber, clay and modified clay pipes, respectively. This study provides an insight into the suitability of known pottery clay soil for the production of clay porous pipes and zeolite significantly improve the hydraulic and performance properties of the produced pipes. For the proposed wetting pattern method, the result revealed that it can appropriately determine wetted dimensions from the analysed images, also the wetted areas recorded a higher range (14.00 - 46.73%) to clay pipes (17.83 - 41.00%). Therefore, conclude that the proposed methods can also provide an alternative for laboratory soil wetting pattern study of different soil types, as well as different soil profiling conditions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN DAN PRESTASI PAIP BERLIANG NANO TANAH LIAT TERUBAH SUAI UNTUK PENGAIRAN SUBPERMUKAAN

Oleh

SALISU ABDULLAHI

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Paip tanah liat adalah secara berterusan mendapat keutamaan bagi pengurusan air pengairan di kawasan yang lebih kering. Walau bagaimanapun, maklumat mengenai pola pembasahan tanah merupakan keperluan utama bagi pemahaman reka bentuk dan pengurusan sistem pengairan subpermukaan, walaupun pendekatan kini secara matematik adalah kompleks. Tujuan kajian ini oleh itu, adalah untuk membangunkan paip tanah liat berliang dan menilai prestasi mereka dan menggunakan paip tersebut untuk menilai prospek kaedah cadangan baharu termografi tanpa-sentuhan bagi kajian pola pembasahan di bawah kondisi eksperimental makmal. Bagi mencapai tujuan ini, tanah tanah liat daripada pit Rege, dan zeolit telah digunakan sebagai bahan mentah bagi pengeluaran paip. Prosedur standard Persatuan Amerika Pengujian dan Bahan (ASTM) telah disorot bagi sifat fizikal tanah, konsistensi dan ujian pengecutan linear. Komposisi kimia sampel, karakteristik morfologikal sampel dan paip yang dikeluarkan telah dianalisis menggunakan Spektroskopi Dispersif Elektron (EDS) dan Mikroskopi Elektron Pengimbas (SEM). Karakteristik geometri, luas permukaan spesifik, isi padu liang, diameter liang, hidraulik dan kapasiti penyerapan paip yang dikeluarkan telah dinilai menggunakan kaedah standard. Tiga jenis paip yang berbeza: getah, tanah liat dan paip berliang tanah liat terubah suai (tanah liat campuran zeolit) telah digunakan bagi kajian pembasahan tanah di makmal menggunakan kolum tanah Plexiglas yang dipek dengan tanah berpasir homogeneous. Kamera inframerah FLIR E60 telah digunakan bagi pemerolehan imej pola pembasahan pada masa pengaplikasian yang berbeza. Kaedah Pengklasifikasian Berselia Algoritma Kebolehjadian Maksimum dalam antara muka perisian 10.7.1 ArcGIS telah digunakan untuk menganalisis imej. Daripada dapatan kajian, tanah yang diperoleh ialah tanah liat dengan 11 % pasir, 34 % kelodak dan 55 % tanah liat, ketumpatan partikel dan ketumpatan pukal masing-masing ialah 2.43 dan 1.58 g/sm^3. Penambahan zeolit menunjukkan penurunan dalam kedua-dua had cecair, had plastik dan pengecutan tanah liat masing-masing daripada 50.7, 27.6 dan 11.67 % kepada 43.7, 27.3 dan 8.92 %, dengan Indeks Keplastikan (PI) daripada 11.67 kepada 8.92. Sampel tersebut merupakan bahan aluminosilikat dengan silika dan alumina sebagai konstituen utama, dan surih besi, potasium dan kobalt. Diameter luaran dan dalaman 12 paip tanah liat berjulat daripada 3.7±0.05 sm dan 2.1±0.05 sm, manakala

12 paip tanah liat terubah suai ialah 3.7±0.12 dan 2.3± 0.22 sm. Paip tanah liat terubah suai merekodkan luas permukaan lebih tinggi, isi padu liang, dan diameter liang masing-masing 4.46±0.20, 0.001044±0.000054 dan 6.29±0.42. Tambahan pula, paip terubah suai tersebut mempunyai kapasiti penyerapan yang tinggi daripada paip tanah liat. Kadar pemancaran paip yang beroperasi pada 0.2 bar masing-masing ialah 2.54, 2.26 dan 2.84 L/h per meter panjang paip getah, paip tanah liat dan paip tanah liat terubah suai. Kajian ini memberikan suatu pemahaman ke atas kesesuaian tanah tanah liat tembikar terkenal bagi pengeluaran paip berliang tanah liat dan zeolit secara signifikan meningkatkan ciri hidraulik dan prestasi bagi paip yang terhasil. Bagi kaedah pola pembasahan yang dicadangkan, dapatan memperlihatkan bahawa, ia sewajarnya dapat menentukan dimensi terbasah daripada imej yang dianalisis, juga luas terbasah merekodkan julat yang lebih tinggi (14.00 - 46.73%) daripada paip tanah liat (17.83 - 41.00%). Oleh sebab itu, kajian menyimpulkan bahawa kaedah yang dicadangkan juga dapat memberikan suatu alternatif bagi kajian pola pembasahan tanah makmal bagi jenis tanah yang berbeza, di samping kondisi pemprofilan tanah yang berbeza.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ArcGIS	Aeronautical Reconnaissance Coverage Geographical Information System
ASAE	American Society of Agricultural Engineers
ASTM	American Society of Testing and Materials
CP	Clay Pipe
CV	Coefficient of Variation
CV_m	Coefficient of Manufactures Variation
DC	Digital images
EDS	Energy Dispersive Spectroscope
FLIR	Forward-Looking Infrared
GIS	Geographical Information system
ITMA	Institute of Advanced Technology
IR	Infrared images
LL	Liquid limit (%)
MAE	Mean Absolute Error
MCP	Modified Clay Pipe
ME	mean error
PI	Plasticity index
PL	Plastic limit (%)
RMSE	Root Mean Square Error
R^2	Regression coefficient
RPP	Porous rubber pipe
RMSE	Root mean square error
SEM	Scanning Electron Microscopy

SL	Shrinkage limit (%)
USDA	United State Department of Agriculture
USCS	Unified Soil Classification System

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Sustainable food production largely depends on how well natural resources are managed (Albaji et al., 2015). Soil and water are natural resources and essential elements in crop production that require effective utilization and good conservation management. With the irrigation sector consuming more than 90 per cent of the global freshwater (Al-ogaidi et al., 2016) water availability continues to decline. A challenging issue that leads to significant in-balance in water allocation among water users (Sepaskhah & Barzegar, 2010), which make farmers use less quality water in many water-scarce areas to meet current and projected future demands. Therefore, become pertinent for the development of various ways that can improve (conveyance, application and storage) the use and management of the available freshwater. As Rezazadeh et al. (2020) posited that inadequacy of freshwater supply, coupled with increasing annual demands, is expected to increase the global demand by 14 % by the year 2025.

The competitive demand is much higher among water users in arid and semi-arid regions where water scarcity is more pronounce (Akhtar et al., 2016; Jlassi et al., 2016). Water scarcity and drought recurrent necessitate the need for beneficial use of irrigation water and its management to improve farmers' water use practices (Nagaz et al., 2012). These numerous challenges call for exploring new irrigation techniques, effective conveyance tools and improved water application approaches for good water management (Albaji et al., 2015). One of such options is adopting efficient irrigation systems offers by micro-irrigation techniques to reduce water losses in irrigated agriculture (Kanda et al., 2020). Hla & Scherer (2003) described micro-irrigation as precise water application methods on or below the soil surface at low pressure with the aid of small devices that can spray, mist, sprinkle, or drip water. The systems design can achieve water conservation (Barragan et al., 2010) through direct application of irrigation water to crop root zone, integrate fertigation, reduce weed and pest infestation, lower capital and operating costs (Madramootoo & Morrison, 2013). Minimize water use, reduces water scarcity and attains optimal yield by producing more crops with less water. Various methods achieved different efficiencies as to yield obtained per water use (Table 1.1).

Table 1.1: Estimated water productivity index for different application devices

Irrigation method	Water Productivity (Kg/m^3)
Closed furrow	0.7
Sprinkler	0.9
Drip	1-2.5
Porous capsule (pressure)	1.9+
Porous capsule (No pressure)	2.5+
Buried clay pot	2.5-7

These various tools involve water application under low pressure and low discharge rate to achieve effective performance, and these techniques are particularly important in arid and semi-arid regions. It ensures slow but frequent water applications to conveniently satisfies plant water requirements. It also aids in conserving soil, nutrient utilization through effective fertilizer and chemicals use, improving crops quality and maximizing productivity, and environmental management, which serves as an alternative approach for sustainable crop production. The techniques allow for crop water application through drip emitters, ceramic tubes, sprayers, porous pipes and bubblers. The low water flow between 0.5 and 0.8 l/h and pressure of between 50 and 400 kPa are the main characteristic (Al-Muhammad et al., 2016) of these techniques.

Various researchers conducted studies on application methods, devices, tools and equipment, water flow, solute transport and soil wetting pattern to enhance irrigation system design, operation, and management to improve micro-irrigation. These tools existed for a long period in drier regions such as pitchers (Abu-Zreig & Atoum, 2004; Bainbridge, 2001; Janani et al., 2011; Pal et al., 2020), rubber porous or perforated (Haijun et al., 2009; H. Liu et al., 2017), moistube (Kimutai et al., 2018), and porous clay pipes (Ashrafi et al., 2002; Igbadun & Barnabas, 2013; Siyal et al., 2011; Siyal et al., 2013). More recent are ceramic moistubes (Cai et al., 2017), trickles and drip emitters (Al-ogaidi et al., 2017; Mohammad Nabil et al., 2016; Yang et al., 2017), bubblers and sprinklers (micro jet, mist spray) that were considered useful tools in micro-irrigation. These techniques ensure slow but frequent water application to irrigate different crops, orchards and vegetables to meet water requirements, maximize water and chemical uses, reduce evaporation, increase yields, save energy, and reduce waste and weeds growth.

Many factors affect water distribution in soils applying with any of these tools. This may include discharge rate, saturated hydraulic conductivity, spacing and placement depth, wetted zone or wetted bulb. Therefore, for effective system design, there is the need to understand the wetting pattern of these irrigation sources, such as line source porous clay pipe irrigation. These resulted in various studies leading to the development of models describing soil wetting patterns for both line and point sources. Most of these models, either mathematically or empirically developed using regression analysis from field and laboratory experimental data or solving flow equations for certain initial and boundary conditions, are usually complex. Hence, call for employing other rapid approaches and can be easily visualized for better understanding even to the nonprofessional groups.

1.2 Problem Statements

Water scarcity necessitates farmers to use various techniques to conserve and ensure water use efficiency in crop production, especially in arid and semi-arid regions. An increase in the uses of sub-surface micro-irrigation systems sees the utilisation of different techniques such as perforated pipes, porous rubber pipes, drip tubing, emitters, ceramic tube and porous clay pipes in water application (Al-ogaidi et al., 2017; Ashrafi et al., 2002; Qiaosheng et al., 2013). Porous rubber pipes and drip emitters dominate the scene as water conveyance and application tools. Siyal et al. (2011) and Madramootoo & Morrison (2013) reported inadequate wetted area and non-uniformity of water application, especially at establishment stage and inefficient water infiltration, among others as problems associated with their usage. Siyal & Skaggs (2009), among others, recommended clay pipes as an alternative tool for effective irrigation water application.

The availability of clay as a primary raw material in porous clay pipes production, coupled with low production cost, ease of installation, labour requirement, and possible usage for several seasons, encourages farmers in many drier areas of the world. On the other hand, clay has a high potential for shrinkage, swelling and compressibility, resulting in cracks. The pipes sometimes take longer to irrigate crops, especially at the establishment stage, among the shortcomings of clay pipes irrigation practices. Also, understanding water flow pattern is important for effective irrigation design, planning and management of surface and subsurface irrigation systems (D. K. Singh et al., 2006). Information on soil wetting pattern studies helps arrive at correct placement depth and spacing, operating pressure to deliver the required amount of water and chemical to the plants. The system was found effective in horticultural, ornamental and landscape applications, covering various tropical, arid, and semi-arid climatic conditions. Its benefits are well-known regarding water and energy conservation, reduced labour, and enhanced fertiliser use (Madramootoo & Morrison, 2013).

Numerous soil wetting pattern studies are related to application tools (drip, trickle and porous pipes), water flow and solute transport phenomena aimed at effective nutrients and chemicals application, good distribution uniformity, and improved performance efficiency. Some studies sighted, for instance, those related to water (quality and type), soil moisture dynamics, mulching, soil texture and profiles, salt accumulation, nitrogen and nitrate in the soil (Al-ogaidi et al., 2016; Hardie et al., 2018; Liu et al., 2015; Moncef & Khemaies, 2016; Siyal et al., 2013; Stirzaker et al., 2017; Zhang et al., 2012; Zhou et al., 2017). Although, there have been many approaches leading to models developments for soil wetting pattern studies. Most of these approaches are mathematically complex, tiresome, destructive in nature, and consumed time to accomplish. In light of this, the need to research using another alternative approach to wetting pattern studies.

Thermal imaging is a non-contact, non-invasive and non-destructive technique used to determine thermal properties and features of any object of interest. Thermal infrared has grown into an important field and is applied directly by users on the ground to acquire images using infrared instruments that are portable and hand-held or by using thermal sensors coupled with optical systems. Thermal imaging data are used directly or indirectly for various applications, which is gaining popularity in recent years with the potential usage in agriculture in the area of nursery monitoring, irrigation scheduling, soil salinity detection, disease and pathogen detection, yield estimation, quality and maturity evaluation and bruise detection. This is made possible due to equipment cost reductions, simple operational procedures and its integration into precision farming.

Therefore, the current study developed porous clay pipes as line sources and used a non-destructive technique for soil wetting pattern determination on homogeneous sandy soil under laboratory experimental conditions.

1.3 Research Objectives

This research aims to develop porous clay pipes, evaluate their performance and used the pipes to test for the effectiveness of the newly proposed imaging technique in wetting pattern determination.

The following are the specific objectives of the study:

1. To characterize the properties of the clay and zeolite as raw materials and morphological properties of the produced pipes.

2. To develop clay pipes and assess the performance of the three different porous pipes (modified clay, clay and rubber).

3. To examine the soil-wetting pattern of three different pipes using thermal imaging technique under subsurface irrigation system.

1.4 Significance of the Study

Irrigation application tools used for micro-irrigation systems are of significant importance to farm engineers, irrigators and managers. With significant success recorded on porous clay pipes as irrigation tools, especially in drier regions, the need for improving such tools becomes imperative. This study highlights the use of nanomaterial (zeolite) as an additive, which is incorporated into the clay soil (an improvement from the conventional clay pipe) for the development of nanoporous irrigation pipes. The produced pipes were used as subsurface line source (unlike drip and trickle used as point sources) system of irrigation and test their performance using wetting pattern study approach. The non-contact technique was used to capture wetting pattern images and utilise classification algorithms to analyse the generated images to determine the wetting geometry.

1.5 Scope and Limitation of the study

This research considers three different porous pipes: a commercially porous rubber pipe, and two locally produced types from clay used for pottery making from Rege, Wudil Local Government of Kano State, Nigeria. The availability of the clay material, the potential area that can support the usage of clay pipes, cheap and availability of source of labour, potters expertise and opportunity for job creation among potters as well as knowledge and information to benefits the locality and the country at large are among the reasons for the choice of the sampling area. One type is made with 100 % clay (porous clay pipe) and the other with clay mixed with zeolite at 3:1 proportion (modifying clay pipe). This study adopted porous clay pipes with the interest of improvement in their production, and adopt the process of utilising imaging techniques and wetting pattern study for evaluating the performances of the produced pipes. The study of soil wetting pattern under laboratory soil column experiment was conducted on homogeneous sandy soil operated on same pressure levels by discharging filtered water through pumping. The research work used FLIR infrared thermal camera to generated digital (DC) and infrared (IR) images. While the supervised classification method on the ArcGIS software interface was used for images analysis.

Sandy soil type was used for this study and the experiment was conducted under laboratory, not field condition. No crop was involved in the experiment and the soil column used is small, but the effect of drawback flow was considered by stopping the supply before the water reaches the end wall. The water was filtered before application but water quality analysis was not considered herein. Other limitations of the image analysis method is that it does not provide direct measurement of dimensions (wetted widths and depths) after analysis, and the method is only limited to laboratory studies for now to provide insight for water movement on soils under consideration.

1.6 Thesis Organisation

The thesis consists of three main parts: preliminary pages; the main body (divided into five chapters and sections) and the supporting pages. The main body was structured into five chapters that include: Chapter one is the general introduction of the study. It further covers the problem statement, research objectives, and significance of the study, scope and limitations. Lastly, it concludes with the thesis organisation. Chapter 2 presents detailed literature, which extensively reviews previous works related to the current research work. It comprises raw materials used, pipes types and concept of wetting pattern study, some of its depending variables studied in the field, laboratory and simulation aspect, using empirical, numerical and analytical modelling concept.

Chapter 3 is composed of descriptions regarding materials needed for the research studies and methods adopted for the conduct of the research work. It describes those procedures for characterisation of soil and zeolite materials used in the production of the pipes, calibration of the commercial rubber porous pipe. It also encompasses a detailed description of where the soil sample was obtained, collection procedures, and the concept of the production of the pipe. Other details include methods involved in conducting the experiment and experimental setup, the process for observation and data collection as well as the tool employed for analysis.

Chapter 4 dealt with the presentations of analyses and discussion of all the results obtained as regards to properties of the raw materials (clay, zeolite), production of the pipes, characterisation of the pipes, and results of the wetting pattern studies. Chapter 5 is the concluding chapter. The final section of the thesis comprises of summary, conclusion, and recommendations as regards the achieved objectives and follows with recommendations for future studies in a way to expand the scope of the work and add more knowledge as related to the field in general. Additional data or any other information obtained from the study not contained in the main body are presented in lists of tables, figures or plates are reported in the appendices.

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BIODATA OF STUDENT

Abdullahi Salisu was born on Monday 23rd July 1973 in Kiru town of Kano State-Nigeria. An alumnus of Ahmadu Bello University (A.B. U), Zaria-Nigeria, He studied Agricultural Engineering and received Bachelor of Engineering degree in 2000. After the completion of mandatory National Youth Service Corp (NYSC) in the Department of Agricultural Engineering, Federal Polytechnic, Kaduna in 2001, Then in 2002 joined the service of Usmanu Danfodiyo University (UDU), Sokoto- Nigeria as Assistant lecturer. An opportunity was accorded to Mr. Salisu that enable him to pursue M. Sc. program in A. B. U. Zaria and obtained M Sc. Eng. (Soil and Water Engineering) in 2009. By Almighty Allah (SWT) grace, Mr. Salisu was selected among those recommended by UDU Sokoto in 2016 for the Tertiary Education Trust Fund scholarship award. This selection offers me the opportunity to enroll into the PhD program (Soil and Water Engineering) in the Department of Biological and Agricultural Engineering tenable at Universiti Putra Malaysia. Abdullahi Salisu is married and blessed with children. Alhamdulillah.

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