ENGINEERING PROPERTIES OF EFFECTIVE MICROORGANISM-BASED TIN SLAG MORTAR

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ABSTRACT

Lately, there has been a global trend of the use of waste materials in construction. Industrial wastes such as tin slag are found in large quantities at landfills in Asia. Their removal will birth a safer environment since these deposits contain metals and radionuclides. Moreover, the use of waste aggregates may significantly affect the properties of mortar. Insufficient strength of mortar produced by natural fine aggregates has necessitated its replacement with other materials such as tin slag. The smoothness and roundness of natural fine aggregate reduces its bond and overall strength of mortar. Therefore, tin slag; with its superior aggregate properties was used as a natural aggregate substitute in this study. However, tin slag contains toxic metals and radionuclide's, which make the material unfit for use without remediation. Effective microorganisms were incorporated in mortar mixes as additive. Independent variables considered are; replacement levels of 0%, 25%, 50%, 75% and 100%, dilution ratios of EM1, molasses and water, EM type (EM1, EM2) and EM to water ratio (EM/W). Hardened properties were determined by compressive strength, flexural strength, tensile strength, water absorption, ultrasonic pulse velocity and expansion tests. The optimum concentrations of EM that maximally improved mortar properties and reduced the concentration of radionuclides were determined. Fresh properties of tin slag mortar indicate that mortar flow increases as tin slag replacement increases. Mechanical properties testing show that optimum replacement is 50% of tin slag. The valorisation of tin slag in mortar reduced concentration of metals drastically below permissible limit, while inclusion of EM as additive further reduces the concentration of metals and radionuclides. EM1 and EM2 performed optimally in terms of mechanical properties and remediation of tin slag, respectively. Mortar mix containing 50% tin slag, 30% fly ash, 10% EM and cured at 50 ºC produced optimum strength.

ABSTRAK

Sejak kebelakangan ini, terdapat trend global penggunaan bahan buangan dalam pembinaan. Sisa industri seperti sanga timah ditemui dalam kuantiti yang banyak di tapak pelupusan sampah di Asia. Penyingkirannya akan melahirkan persekitaran yang lebih selamat kerana mendapan ini mengandungi logam dan radionuklid. Selain itu, penggunaan agregat sisa boleh menjejaskan sifat mortar dengan ketara. Kekuatan mortar yang tidak mencukupi yang dihasilkan oleh agregat halus semulajadi memerlukannya diganti dengan bahan lain seperti sanga timah. Kelicinan dan kebulatan agregat halus semulajadi mengurangkan ikatan dan kekuatan keseluruhan mortar. Oleh itu sanga timah; dengan sifat agregat unggulnya telah digunakan sebagai pengganti agregat semula jadi dalam kajian ini. Walau bagaimanapun, sanga timah mengandungi logam toksik dan radionuklid, yang menjadikan bahan itu tidak sesuai untuk digunakan tanpa pemulihan. Mikroorganisma yang berkesan telah dimasukkan ke dalam campuran mortar sebagai bahan tambahan. Pembolehubah bebas yang dipertimbangkan ialah; aras penggantian 0%, 25%, 50%, 75% dan 100%, nisbah pencairan EM1, molase dan air, jenis EM (EM1, EM2) dan nisbah EM kepada air (EM/W). Sifat keras ditentukan oleh kekuatan mampatan, kekuatan lentur, kekuatan tegangan, penyerapan air, halaju denyutan nadi, ujian pengembangan dan pengecutan. Kepekatan optimum EM yang meningkatkan sifat mortar secara maksimum dan mengurangkan kepekatan radionuklid telah ditentukan. Sifat segar mortar sanga timah menunjukkan bahawa aliran mortar meningkat apabila penggantian sanga timah meningkat. Ujian sifat mekanikal menunjukkan bahawa penggantian optimum ialah 50% sanga timah. Valorisasi sanga timah dalam mortar mengurangkan kepekatan logam secara drastik di bawah had yang dibenarkan, manakala kemasukan EM sebagai bahan tambahan mengurangkan lagi kepekatan logam dan radionuklid. EM1 dan EM2 berprestasi dengan baik secara optimum dari segi sifat mekanikal dan pemulihan sanga timah masing-masing. Campuran mortar yang mengandungi 50% sanga timah, 30% abu terbang, 10% EM dan diawet pada 50 ºC menghasilkan kekuatan optimum.

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LIST OF ABBREVIATIONS

As	.	Arsenic
$Ca(OH)_2$	.	Calcium Hydroxide
CH_3CH_2OOH	.	Acetic acid
CO_2	.	Carbon dioxide
Cr	-	Chromium
EDX		Energy Dispersive X-Ray
EM	-	Effective Microorganisms
EMA	-	EM Activated
GHG	-	Green House Gas
ICPOES	-	Inductively Coupled Optical Emission Spectrometer
MCCP	-	Microbial Calcium Carbonate Precipitation
Mo	-	Molybdenum
NaOH	-	Sodium Hydroxide
Pb	-	Lead
SEM	-	Scanning Electron Microscopy
SPLP	-	Synthetic Precipitation Leaching Procedure
TENORM	-	Technologically Enhanced Naturally Occurring Radioactive Material
TGA	-	Thermo-Gravimetric Analysis
UPV	-	Ultrasonic Pulse Velocity
USEPA	-	United States Environmental Protection Agency
WHO	-	World Health Organization
WQI	-	Water Quality Index
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence
ZHE	-	Zero-Headspace Extraction vessel
Zn	-	Zinc

LIST OF SYMBOLS

A	-	Area of load
CRD	-	Comparator readings
d	-	Diameter of specimen
D_{avg}	-	Average base diameter
D_o	-	Original base diameter
fc	-	Compressive strength
G	-	Gauge length
L	-	Final comparator reading
L_0	-	Initial comparator reading
Lt	-	Distance between transducers
ΔLx	-	change in length
m	-	Mass of composites
P	-	Ultimate compression load
r	-	Radius
Sf	-	Flexural strength
Vp	-	Pulse velocity
T	-	Effective transit time
Ts	-	Splitting tensile strength
V	-	Volume of composites
Vp	-	Pulse velocity
Wa		Percentage of water absorption
W1		weight of sample after immersion
W2		Weight of oven dried sample

CHAPTER 1

INTRODUCTION

1.1 Introduction

Mortar is one of the most used materials worldwide, alongside concrete. Mortar is an essential composite for brick work, plastering and rendering. Globally, rapid infrastructural growth has increased the demand for cement mortar. Unfortunately, there are no exact measures of the quantity of mortar used worldwide, annually. However, about 4 billion tons of cement are produced annually (Wang, 2019) and a ton of cement produced, results in the release of about a ton of carbon dioxide (CO_2), which contributes to global warming (Chen *et al.*, 2010). This large volume of cement is majorly utilized for concrete and mortar. Thus, it is necessary to ensure the sustainable usage of mortar by reducing the use of cement while its toughness is maintained. Good mortar should optimally achieve functionality, strength and reliability throughout its entire design life. This reduces the probability of reconstruction and thus reducing cement usage and global warming.

On the other hand, cost effective and sustainable mortar can be produced by utilizing wastes as aggregate replacement materials. The use of waste aggregates reduces the cost of mortar production and significantly affect the properties of mortar. The composition of mortar influences the behavior of engineering structures in terms of strength and protection against water and deleterious substances. However, its long-term performance depends on the interactions with the service environment (Basheer *et al.*, 2001). Thus, materials and additives that can produce good mortar must be harnessed for sustainable construction. The emphasis however is on materials that satisfy social, economic and environmental requirements (Kibert, 1994). Sustainable mortar can be achieved by the use of materials, such as industrial wastes. Industrial wastes are readily available and cost-effective, so can be harnessed to reduce the pressure on natural fine aggregate (NFA), thereby promoting sustainability.

1.2 Problem Background

Due to the growing concerns regarding climate change, environmental pollution among other factors, sustainable construction has been at the forefront worldwide. The use and efficacy of cement replacement materials and additives has been extensively studied. This decreases the negative impacts of the continued rise in carbon footprint, which among other things resulted in global warming. Mortar materials such as aggregates also have harmful environmental consequences. The effect has been deforestation, marine biodiversity, global warming, disruption to shoreline infrastructure and global coastal fishing. Reducing the consumption of natural aggregates by looking out for alternative materials for its replacement is highly necessary. Research show that waste materials, such as; steel slag (Zhao *et al.*, 2018), lead slag (Ogundiran *et al.*, 2013), copper slag (Prem *et al.*, 2018) have similar properties to natural fine aggregate. Thus, focus has been on the use of wastes for aggregate replacement. Moreover, they are found in large quantities on landfills. The utilization of wastes in mortar is a cheap remedy for environmental pollution as well as improvement of properties of cement composites.

Industrial wastes are mostly land-filled, chemically treated, or kept at repositories. Disadvantages of such disposal methods include cost and the unavailability of useful landmasses (Yang *et al.*, 2018). Waste stockpiles have been linked to carbon dioxide emissions, as greenhouse gases are emitted from waste landfills (Deepa *et al.*, 2019). Also, many industrial wastes contain high amounts of radionuclides which are dangerous to humans and the entire eco-system (Drinčić *et al.*, 2017). Likewise, leaching of metals from these industrial wastes at landfills remains a major challenge especially in dynamic or extreme environments where very high or low pH are prevalent. For sustainable use of wastes in mortar these shortcomings must be addressed.

Nowadays, waste valorisation is commonly used as a sustainable channel for reuse and recycling of industrial wastes. Valorisation is advantageous due to the low remediation cost, environmental and construction benefits. This is so because the encapsulation material is already provided by the cement composites, thus there is no added cost for encapsulation. This method provides for free a conduit for waste containment. Many studies have been conducted to establish the efficacy of industrial wastes such as steel slag (Zhao et al., 2018), lead slag (Ogundiran et al., 2013), copper slag (Prem et al., 2018), foundry sand (Prasad *et al.*, 2018), and recycled glass (Tamanna *et al.*, 2020) as fine aggregate replacement material. For example, Zhao et al. (2018) replaced 20% of fine aggregate in concrete with steel slag. The replacement showed that compressive strength was improved by 28% over control concrete sample. Similarly, copper slag was used up to 100% as fine aggregate replacement by Prem et al. (2018). It was observed that 100% copper mortars had 3% compressive strength above control mortars replacement. The use of foundry sand and recycled glass at 10% replacement, has also been found to improve the mechanical properties of concrete (Pandey *et al.*, 2015; Kashani *et al.*, 2019).

Another such industrial waste readily available and under-utilized is tin slag (TS). About 2 million tons of TS waste is lying idle at landfills is found worldwide, with about 50% of these deposits found in China (Izard & Müller, 2010). Very few studies have been conducted on the use of TS as replacement for fine aggregate. The compressive strength test showed that samples attained strength of 125.07 MPa. Hashim et al. (2018) applied TS as replacement of fine aggregate to produce pavement interlocking bricks. The study showed that the compressive strength increased by 20%, however, the study considered only 100% and 20% TS replacement of fine aggregate(Hashim *et al.*, 2018). Likewise, Rustandi et al (2018) utilized the pozzolanic properties of TS by replacing 10% of cement. The TS mortar achieved only 63% compressive strength of the control sample at 28 days (Rustandi & Cahyadi, 2018).

The drive towards sustainability has propelled the use of green materials such as microorganisms. Research studies have utilized microorganisms for improvement of concrete properties (Seifan *et al.*, 2016; Basha *et al.*, 2018; Sonali *et al.*, 2019) while few researchers have studied the contribution of microorganisms in mortar (Zha *et al.*, 2018). Most common microorganisms are cultured organisms, especially of the bacillus genera (Meera and Subha, 2016; Bhagyashri *et al.*, 2017; Jagannathan and Satya, 2018). However, Effective Microorganisms (EM); which is a combination of many microorganisms has been scantily used (Ismail and Kamaruddin, 2014). EM is in an already prepared form, so can be added directly in mortar. Studies have shown that EM may improve compressive strength of mortar up to 30% (Ali *et al.*, 2017), invariably the emission of CO_2 in relation to cement use will be reduced by EM modification and by prolonging the service life of mortar. Another aspect few researchers have tested the capability of microorganisms is the remediation of radionuclides (Sasaki *et al.*, 2012).

The incorporation of TS into cement composites can foster green construction and reduce environmental pollution, especially with the incorporation of EM. It may help to minimise the sole dependence on NFA material, thus reducing the depletion rate of this resource and the negative environmental effects caused by sand mining. The valorisation of waste in mortar may be an effective way to engender sustainability of materials, cost effectiveness and durability of mortar.

1.3 Problem Statement

The replacement of Natural Fine Aggregate (NFA) with materials such as wastes have lately become necessary, not just because of the adverse environmental effects of waste, but also due to their contribution to the engineering properties of mortar. The smoothness and roundness of NFA reduces the compactness of cement composites as compared to some waste materials such as TS. However, the high radionuclide concentration of heavy metals present in TS poses a threat to its sustainable use; therefore, sustainable methods to reduce the radionuclide concentration to acceptable limits must be harnessed. Recent finding confirms that certain microorganisms can absorb radionuclides and degrade them using different methods including biosorption and bioaccumulation. Researchers have utilized cultured microorganisms for the removal of toxic elements in soils. Likewise others have studied the use of microorganisms to improve concrete properties (Bachmeier *et al.*, 2002; Wang *et al.*, 2016). Engineering properties have been improved according to past researches (Yatim *et al.*, 2009) by different microorganisms including both cultured and product microorganisms like EM. However, the effects of EM on properties of mortar have been scantily studied. This research work intends to utilize effective microorganisms (EM) to remediate and improve mortar properties using TS to replace natural fine aggregate (NFA). In order to evaluate the hardened and remedial properties of EM based TS mortar, a comprehensive study was carried out to develop the most favourable EM-based TS mortar.

1.4 Research Aim

The research work aims at developing a sustainable and radiation free EM based TS mortar.

1.4.1 Research Objectives

The objectives of the research are:

(a) To assess the physio-chemical characteristics and mix design of TS mortar.

(b) To evaluate the engineering and micro structural properties of TS mortar.

(c) To investigate the remediation capacity of EM in TS mortar.

1.5 Scope of Research

In order to ascertain that TS is fit to be used for mortar, leaching test was conducted. Since TS is a waste material, the Toxicity characteristic leaching procedure (TCLP) test was employed to study its leaching characteristics.

The optimum water content for TS mortar was ascertained by varying water to binder ratio across all replacement levels (0%, 25%, 50%, 75%, 100%). This was evaluated using workability and compressive strength results. Other mechanical tests were ascertained using the optimum water/cement (w/c) ratio. Engineering properties that were measured are compressive, tensile and flexural strengths, water absorption, expansion and shrinkage tests.

The various ranges adopted per variable are justified as follows:

NFA replacement (%): Scanty studies available so far, show that 30% is the optimum replacement in cement composites, but since microbial modification can improve mortar properties, higher concentration of TS may give better results. Also, TS effect when used as mortar constituent has not been reported in literature, thus a wider range will provide better assessment of the behaviour of TS mortar.

Dilution ratios of EM, molasses and water: Most studies that have utilized EM in cement-based composites have used the basic dilution ratio (5:5:90) used for agriculture (Hu & Qi, 2013; Norsyaza & Abdul Rahman, 2015). Since molasses provides food for microorganisms, more molasses may lead to better EM survival and improvement in mortar properties.

EM type: Most studies have utilized EM1 in mortar and cement composites. The effect of other EM types has rarely been studied. Addition of EM2; which contains predominantly photosynthetic bacteria, may help prolong the life of other microbes and vice versa by their metabolites.

1.6 Significance of Study

i. EM is a combination of beneficial microorganisms that can reduce the amount of radiation in our environment due to their ability to absorb radionuclide's thereby contributing to green construction.
ii. The addition of EM and TS improves the engineering properties of TS mortar
iii. TS is a waste that contains radioactive elements which makes it an unwanted material within dwellings and the environment in general. This research will provide a cheap, safe and sustainable method that will afford the use of TS waste in cement composites.
iii. Its utilization as a partial or complete replacement material by the use of EM will help turn waste to wealth thus reduce depletion of non-renewable NFA and make stockpiling destinations free for utilization.

1.7 Flow of the Thesis

The thesis was prepared according to the Universiti Teknologi Malaysia template. The thesis consists of seven chapters.

Chapter one: A general introduction of mortar and their sustainability was presented in this chapter. The background and problem statement were also explained. This chapter also presents the study research aim, objectives, scope and significance.

Chapter two: Information about previous research works were presented in this chapter. General discussion on green composites was done. Previous findings on TS concrete and EM-based cement composites were also discussed.

Chapter three: This chapter explains the materials and test methods used for testing in accordance with the appropriate standards.

Chapter four: The results and discussion of physical, chemical and micro-structural properties of materials used in this study was discussed in this chapter.

Chapter five: Chapter 5 presents the results of the engineering and micro-structural properties of TS mortar and EM-based TS mortar

Chapter six: This chapter presents the results of toxicity and radionuclide concentration. The chapter generally shows the remediation capacity of EM in TS mortar

Chapter seven: The conclusions and recommendations of this study were highlighted in this chapter. This includes research outcomes and recommendations for future studies.

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