PHYSICAL AND MECHANICAL PROPERTIES OF REACTIVE POWDER CONCRETE CONTAINING WASTE GLASS AND DATE PALM FIBER

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DEDICATION

I dedicate this thesis for my beloved family who did not stop their daily supporting since I was born, my dear mother and father, my husband and kids. They never hesitate to provide me all the facilities to push me forard as much as they can. This work is a simple and humble reply to their much goodness I have taken over during that time. Furthermore, my brothers, and sisters. My grandmother and grandfather (Allah's mercy them).

ABSTRACT

Reactive powder concrete (RPC), composed of portland cement, silica fume, quartz, steel fiber, and a low water-to-binder ratio, exhibits exceptional mechanical and durability properties. However, RPC is prone to thermal spalling at high temperatures due to its dense microstructure. Additionally, the high cost of silica fume presents challenges for using locally available materials. This study evaluates the effects of replacing silica fume with waste glass powder on RPC's physical, mechanical, and high-temperature properties. It also investigates the use of date palm fibers to enhance high-temperature stability. The effect of date palm fibers utilization on the RPC's physical, mechanical properties high-temperature stability were assessed and the spalling behavior of RPC containing waste glass and date palm fiber were analyzed. Six RPC mixes were prepared: waste glass fully replaced silica fume, and date palm fibers partially replaced steel fibers, with a total fiber volume fraction of 2%. Specimens were cured for 3, 7, and 28 days, and their modulus of rupture, splitting tensile strength, and modulus of elasticity were tested according to ASTM C 78-02 and ASTM C 496-04. High-temperature performance was assessed using a fire flame test up to 600°C. Results show that while waste glass powder improves mechanical properties, spalling at high temperatures persists. The addition of date palm fibers significantly improves RPC's high-temperature stability, reducing spalling despite a slight decrease in mechanical properties. The best performance was achieved with RPC containing an equal volume of steel (1%) and date palm fibers (1%), which exhibited stability and no spalling. In contrast, RPC with only steel fibers experienced explosive spalling at 600°C. The enhanced performance with date palm fibers is attributed to the reduced density and less dense structure of the RPC. Thus, a hybrid mix of steel and date palm fibers is proposed for high-temperature applications due to its improved stability.

SIFAT FIZIKAL DAN MEKANIKAL KONKRIT SERBUK REAKTIF YANG MENGANDUNGI SISA KACA DAN GENTIAN POHON KURMA

ABSTRAK

Konkrit serbuk reaktif (RPC), yang terdiri daripada simen portland, wasap silika, kuarza, gentian keluli, dan nisbah air kepada pengikat yang rendah, mempamerkan sifat mekanikal dan ketahanan yang luar biasa. Walau bagaimanapun, RPC terdedah kepada serpihan terma pada suhu tinggi kerana struktur mikronya yang padat. Di samping itu, kos wasap silika yang tinggi memberikan cabaran untuk menggunakan bahan-bahan tempatan. Kajian ini menilai kesan penggantian wasap silika dengan serbuk kaca sisa pada sifat fizikal, mekanikal dan suhu tinggi RPC. Ia juga menyiasat penggunaan gentian kurma untuk meningkatkan kestabilan suhu tinggi. Kesan penggunaan gentian kurma ke atas sifat fizikal, mekanikal RPC kestabilan suhu tinggi telah dinilai dan tingkah laku serpihan terma RPC yang mengandungi sisa kaca dan gentian kurma telah dianalisis. Enam bancuhan RPC telah disediakan: kaca sisa menggantikan sepenuhnya wasap silika, dan gentian kurma menggantikan sebahagian gentian keluli, dengan jumlah pecahan volum gentian sebanyak 2%. Spesimen telah diawetkan selama 3, 7, dan 28 hari, dan modulus kepecahan, kekuatan tegangan pemecahan, dan modulus keanjalannya telah diuji mengikut ASTM C 78-02 dan ASTM C 496-04. Prestasi suhu tinggi dinilai menggunakan ujian nyalaan api sehingga 600°C. Keputusan menunjukkan bahawa sementara serbuk kaca sisa meningkatkan sifat mekanikal, serpihan pada suhu tinggi berterusan. Penambahan gentian kurma meningkatkan dengan ketara kestabilan suhu tinggi RPC, mengurangkan serpihan walaupun sedikit penurunan dalam sifat mekanikal. Prestasi terbaik dicapai dengan RPC yang mengandungi isipadu keluli yang sama (1%) dan gentian kurma (1%), yang mempamerkan kestabilan dan tiada serpihan. Sebaliknya, RPC dengan hanya gentian keluli mengalami letupan letupan pada 600°C. Prestasi yang dipertingkatkan dengan gentian kurma adalah disebabkan oleh ketumpatan yang berkurangan dan struktur RPC yang kurang padat. Oleh itu, campuran hibrid keluli dan gentian kurma dicadangkan untuk aplikasi suhu tinggi kerana kestabilannya yang lebih baik.

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صدق الله العلي العظيم

سورة العلق (1-5)

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LIST OF ABBREVIATIONS

B	-	Blast furnace slag
C	-	Cement
C-S-H	-	Calcium Silicate Hydrate
DPF	-	Date palm fiber
EA	-	Early Age
ECC	-	Engineered Cementitious Composites
F	-	Fly ash
HPC	-	High performance concrete
HSC	-	High strength concrete
IQ	-	Iraqi Specification
NF	-	Natural fibers
OC	-	Ordinary concrete
PP	-	polypropylene fiber
PVA	-	Poly-vinyl alcohol fiber
RHA	-	Rice husk ash
RPC	-	Reactive powder concrete
S.F	-	Silica fume
SCC	-	Self compactingconcrete
SCMs	-	Supplementary cementing materials

UHPC	-	Ultra high performance concrete
W/B	-	Water to binder ratio
WGP	-	Waste glass powder
XRF	-	X-ray fluorescence

LIST OF PUBLICATIONS

This study grants an account of the study undertaken by the authors. Some articles have been presented as follows:

1. Rasoul, Z.S., Juoi, J.M., Mohamad, M. and Kadhum, M.M., 2018. Density and Spalling behavior of Reactive Powder Concrete after Exposure to Fire Flame. *Proceedings of Innovative Research and Industrial Dialogue*, pp. 124–125. (Published).
2. Rasoul, Z.S., Juoi, J.M., Mohamad, M. and Fawzi, N.M., 2020. Date palm fiber(DPF) and its composites: A comprehensive survey. *International Journal of Advanced Science and Technology*, Vol. 29(19), pp. 1776–1788. (Published) Scopus.
3. Rasoul, Z.S., Juoi, J.M., Al-Abbas, B.H. 2023. Mechanical Properties and High Temperature Performance of Sustainable Reactive Powder Concrete Containing Waste Glass. *Journal of Advanced Research in Applied Mechanics*, 112(1), pp. 149–161 (Published) Scopus.

CHAPTER 1

INTRODUCTION

1.1 Background

Reactive Powder Concrete (RPC) is a type of High-Strength Concrete (HSC) developed in the 1990s. Despite of the outstanding mechanical performance, RPC used to suffer a severe failure known as thermal spalling when exposed to elevated temperatures higher than 600 °C, which often causes a devastating explosion. This is due to its dense microstructure that is vulnerable to explosive spalling at elevated temperatures, and seriously jeopardizes the safety of RPC application (Ju et al., 2016).

The aim of this study is to reduce the density of reactive powder concrete as well as saving other mechanical and physical properties within the acceptable levels. This is done by introducing agricultural waste fiber (date palm fiber) and replacing silica fume with waste glass powder in the RPC mixture. The waste utilization helps in reducing the production cost of the RPC and saves the environment by reducing raw materials' consumption.

Reactive Powder Concrete is a new class of material developed due to the advancements of modern concrete technology. Dense microstructure of RPC prevents evaporation and escape of free water from the interior portion of RPC specimen at elevated temperatures. Explosive spalling occurs when the pore pressure in the matrix accumulates to a threshold, exceeding the tensile strength of concrete (Hiremath and Yaragal, 2018).

Efforts were accomplished by previous researchers to solve spalling problem. Few researchers work on adding steel fiber with various percentages in RPC mix (Pang et al., 2011) and (Yan et al., 2016); however spalling is still reported. Others tried to dry RPC samples before fire tests in order to minimize free water inside the RPC microstructure (Gong et al., 2017), (Alrekabi et al., 2017) and (Hou et al., 2017); but this approach is not applicable in large span and building applications. On the other side some researchers study the effect of Polypropylene (PP) fiber on the spalling behaviour of RPC. PP fiber can prevent spalling but has adverse effect on mechanical properties (Hiremath and Yaragal, 2018). The effect of hybrid reinforced (steel+ PP) fiber (Canbaz, 2014) (So et al., 2015), (Jang et al., 2016) or (steel+ Poly-Vinyl Alcohol PVA) fiber (Sanchayan & Foster, 2016) on spalling of RPC was also studied by different researchers with the used heat release function and this approach is also not applicable in large span and building applications.

Generally, reactive powder concrete is regarded as an ultra-dense mixture of silica fume, water, Portland cement, fine quartz sand, superplasticizer, quartz powder, and steel fibers. Thus, it is a challenge to produce the high performance RPC for structural applications from local available materials due to least costly components of conventional concrete are eliminated by more expensive elements such as the silica fume, quartz sand and quartz powder. Moreover, RPC production from these materials is facing additional raw material expenses and time during the import process for local constructions as reported in (Demiss, Oyawa and Shitote, 2018), (Vigneshwari et al., 2018) and (Allahverdi et al., 2018).

In addition, the high dosage of both Portland cement and silica fume in high performance concretes, not only increases the cost, but also represents a significant drawback regarding sustainability due to consumption of raw materials (Asteray et al., 2017), (Demiss et al., 2018) and (Sui et al., 2018). Therefore, RPC manufacturing needs to be designed based on economical material that produces high strength to weight ratio and high thermal resistance concrete (So et al., 2015).

Globally, 90 billion tons of solid wastes are expected to be generated annually by the year 2025 (Asteray et al., 2017). However, as a major opportunity, there is a market demand for sustainable eco-friendly materials and design concepts using recycled wastes which require little energy to process; and enabling the reuse of these waste materials in a continuous cycle. At present, million tons of glass is being dumped every year all over the world. Although it is a recyclable material once it is mixed in different colours, it becomes useless for recycling. More than 75% of glass is basically composed of silica and due to a chemical component; the glass could be a suitable material to be used as a replacement of cement in concrete. When the glass is pulverized up to micro particle sizes, it performs pozzolanic reaction and leads to the formation of the high amount of C–S–H productions in cementitious mixtures (Mosaberpanah, Eren and Tarassoly, 2018).

Also, much waste from the agriculture industry are usually either burnt or land-filled and these cause environmental issues such as pollution and contamination (Mo et al., 2016). Date Palm Fiber (DPF) is one of the waste materials in agriculture sector, which is widely grown in Middle East (Ghori et al., 2018). The availability of these natural waste fiber materials is a potential to be utilized in introducing pores in reducing the high density of RPC, hence improving its spalling behaviour at 600 ℃ application. At present, very limited work is carried out in studying the effect of natural waste fiber on the performance of RPC.

1.2 Problem statement

The research problem formulated for this thesis is based on the need to enhance the stability and the thermal resistance of reactive powder concrete (RPC) under high temperature 600 ℃ (Abdul-Rahman et al., 2020). Concerns are on materials design that made the spalling, the high cost, by use sustainable materials are of most interest. In addition, it is also of interest to design a sustainable RPC that reduce the consumption of raw material resources. Hence research does also envolved; how does using waste glass powder (replacing silica fume) affect the physical, mechanical and thermal properties (particularly stability at 600 ℃) of reactive powder concrete?;how does waste glass powder and date palm fiber affect the physical, mechanical and thermal properties (particularly stability at high temperature) of reactive powder concrete? and how does natural fiber incorporation affect the spalling behaviour of sustainable reactive powder concrete at high temperature?. Therefore, to fulfil the above gaps, reactive powder concrete from local wastes is developed in this study with an aim for the produced RPC to be utilized as a proper construction material in the emerging concrete technology for future civil engineering projects.

1.3 Research objectives

The aim of this study is to develop reactive powder concrete based on local natural and solid wastes. Thus the objectives of this research are:

1. To evaluate the impact of substituting silica fume with waste glass powder on the RPC's physical, mechanical properties high-temperature stability.
2. To develop RPC incorporating waste glass and date palm fibers for improved high-temperature stability.

3. To assess the effect of date palm fiber utilization on the RPC physical, mechanical properties high-temperature stability.

4. To analyze the spalling behavior of RPC containing waste glass and date palm fiber.

1.4 Research scopes

The scopes of this research are to utilize agricultural wastes (date palm fiber) (up to 2 vol. %) as a partial replacement of steel fiber and waste glass powder as a total replacement of silica fume. This study is focusing on the production of reactive powder concrete samples before and after an-exposure at 600 ℃ as well as the physical properties (density, colour), mechanical properties (compressive strength, splitting tensile strength and flexural strength) and thermal properties (spalling) of the reactive powder concrete and saving the total fiber used with 2 vol. %.

1.5 Contributions

The work has included several contributions in the area of construction materials in general and sustainable RPC in particular as in the following:

1-This study is the first that has proposed reactive powder concrete using the concept of replacement of silica fume (one of the most expensive material in RPC mix). Waste glass powder is used as a full replacement to silica fume as an effort for cost reduction and enables adaptability to the recycled materials to be useful and reduce their negative effect on the environment and the nature.

2- This study has extended the feature space that the majority of the works in the literature used for reactive powder concrete for using it safely at high temperature applications.

Agricultural waste (date palm fiber) was used as a partial replacement to steel fiber to solve the spalling problem in reactive powder concrete after exposure at 600 ℃.

3- This study is one of the effective approaches that tackle the aspect of reactive powder concrete after exposure to real fire flame, which has not been under focus in the other approaches of RPC at high temperature 0f 600 ℃.

4- This study proposed reactive powder concrete design with no spalling at 600 ℃.

1.6 Organizations of the thesis

The research work in this study is presents in five chapters, as follows:

Chapter One presents a general introduction about the high temperature stability of fire problem of reactive powder concrete. Chapter Two includes a review of relevant literature focussing on the composition and mechanical properties of RPC, the behaviour of concrete partitions at elevated temperature, fire conditions and use of fibers to prevent spalling. Also, it discusses previous studies on the effect of recycled materials inclusion via different ways on reactive powder concrete's physical, mechanical and thermal properties. In Chapter Three, the methodology that involved details of the materials used through this work to construct the samples, mixing and placing procedures, equipment details, instrumentation, and test procedures carried out in this study are presented. Also, it includes a description and details of experimental work and testing setup. In Chapter Four, the results of the experimental tests are presented together with their comprehensive analysis and discussion. Finally, Chapter Five summarizes the main conclusions of present research and gives recommendations for future work.