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Review

High temperature and residual properties of reactive powder concrete – A review

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HIGHLIGHTS

- High temperature and residual properties of RPC were reviewed.
- The properties of RPC were compared with provisions of design codes.
- Mechanism of fire induced spalling and various influencing factors were reviewed.
- Steel fibres improve the spalling resistance and thermo-mechanical properties.

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ABSTRACT

Reactive powder concrete (RPC) is highly susceptible to serious damages and explosive spalling during high temperature owing to its dense microstructure. Over the past few years, the demand of RPC in construction industry increased due to ultra-high strength and durability requirements. This raises concerns about fire resistance of RPC. Recently, numerous studies have been carried out to explore the residual and hot-temperature performance of RPC. Within this framework, the experimental results about the thermal, mechanical and deformation properties of RPC at both test modalities are compiled and compared. Important mechanical properties focused in this paper are compressive strength, tensile strength, flexural strength, elastic modulus and stress-strain behaviour. Among thermal and deformation properties; thermal conductivity, specific heat capacity, mass loss, free thermal strain and load-induced thermal strain are discussed. Meanwhile, mechanism of fire induced spalling and its influencing factors like moisture content, water-binder ratio, fibres and supplementary cementitious materials are studied as well. A relationship among spalling critical temperature and standard cube compressive strength has been developed. Furthermore, the relationship among spalling resistant steel fibres dosage with standard cube compressive strength has been obtained. A comparison of compiled fire resistance data of RPC with existing code provisions is also presented. These code provisions are found to be more conservative for residual test data rather than hot-temperature test data. The residual strength of RPC after exposure to high temperature was relatively higher than hot-temperature strength at most temperature ranges. This study shows a lack of experimental data about deformation and thermal properties of RPC exposed to high temperature. Overall, those factors have been highlighted in the paper that improve high temperature performance of RPC.

Contents

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Nomenclature

f_{cu}^T, f_{cu}	cubic compressive strength of RPC at high and room temperature, respectively
f_c^T, f_c	prism compressive strength of RPC at high and room temperature, respectively
f_t^T, f_t	tensile strength of RPC at high and room temperature, respectively
f_f^T, f_f	flexural strength of RPC at high and room temperature, respectively
E_c^T, E_c	tangent modulus of RPC at high and room temperature, respectively
E_p^T, E_p	secant modulus of RPC at high and room temperature, respectively
σ, ε	stress and strain of RPC
$\varepsilon_c^T, \varepsilon_c$	peak strain of RPC at high and room temperature, respectively
$\varepsilon_{tr}, \varepsilon_{th}$	transient strain and free thermal strain of RPC, respectively
T, ρ	fire temperature in degree Celsius and volumetric percentage of fibres in concrete
λ, C_v	thermal conductivity and specific heat capacity of RPC, respectively

1. Introduction

Reactive powder concrete (RPC) is the new generation of concrete with ultra-high strength, remarkable durability and high toughness. The outstanding mechanical properties achieved are compressive strength, Young's modulus and fracture energy in the range of 200–800 MPa, 50–75 GPa and 12–40 kJ/m^2, respectively [1–2]. Fine particles of silica fume and quartz powder with low water-to-binder (w/b) ratio give ultra-high strength and toughness to RPC [3]. Exclusion of coarse particles improves the homogeneity of RPC, whereas fibres improve ductility. Owing to these remarkable properties, RPC has been used in diverse engineering fields such as civil, municipal, nuclear power, petroleum, marine and military structures [4–6]. With increasing demand, its commercial production has also started in many countries such as Australia [6], Canada [7], China [8], France [9], South Korea [10] and United States [11]. However, the performance of RPC in real life fire still needs to be explored.

Generally, Concrete is an inert material whose performance at high temperature is better than other construction materials, such as timber and steel, due to its non-combustibility and low thermal conductivity [12]. However, the virtual absence of capillary pores in RPC makes it more prone to explosive spalling. Theoretically, increasing vapour pressure and non-uniform thermal gradient are the key causes for explosive spalling of RPC at high temperature.

Recently, numerous studies have been carried out to investigate hot-temperature and residual properties of RPC. However, no updated guidelines are available about fire resistance behaviour of RPC in current and old design codes. Even the review reports about the properties of RPC at high temperature are scarce. Within this framework, the authors provided a comprehensive and updated report about the hot-temperature and residual properties of RPC. The important mechanical parameters discussed are compressive strength, tensile strength, flexural strength, elastic modulus and stress-strain relationship. Thermal properties debated are thermal conductivity, specific heat capacity and mass loss. Whereas, deformation changes like free thermal strain (FTS) and load-induced thermal strain (LITS) are also reviewed at high temperature. Fire resistance performance of RPC is compared with provisions of codes for normal strength concrete (NSC) and high strength concrete (HSC) such as Eurocode-2 [13], ACI code [14], ASCE manual for fire structural protection [15] and Concrete Association of Finland guidelines [16]. Meanwhile, factors influencing spalling and its mechanism are also discussed. Among other factors which affect the performance and spalling of RPC at and after high temperature such as w/b ratio, moisture content, fibres and supplementary cementitious materials (SCMs) are also discussed. Relationships have been developed from published data among spalling critical temperature and standard cube compressive strength, spalling resistant steel fibre dosage and standard cube compressive strength at ambient temperature. Overall, those factors have been outlined in the paper that improve high temperature and residual performance of RPC.

2. Effect of temperature on mechanical properties of RPC

The important mechanical properties of concrete which are used for fire resistance performance include compressive strength,