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Mechanical Properties and High Temperature Performance of Sustainable Reactive Powder Concrete Containing Waste Glass

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ABSTRACT

At present, it is a challenge to produce a high performance reactive powder concrete (RPC) from local available materials due to the least costly components of a conventional concrete are eliminated by more expensive elements such as the silica fume and steel fibers. In the other hand, million tons of glass is being dumped every year all over the world. More than 75% of glass composition is basically silica and reported to having a pozzolanic reaction. Thus, glass is potentially suitable material as replacement materials for the RPC mixture. In our work, waste glass powder (WGP) was used to completely replace silica fume. Compressive strength, splitting tensile strength, flexural strength and elastic modulus measurements were reported along with the density and colour of the RPC produced. The highlight of this study is on the assessment of the RPC at high temperature tested by direct burning at 600˚C. This had addressed to a very limited reported finding on the high temperature performance of RPC utilizing waste materials. It was found that, RPC containing waste glass powder changes the colour of RPC from darkish grey to light grey. Adding waste glass powder had reduced the density of RPC by (0.05) gm/cm^3. Using waste glass powder instead of silica fume had also improves the mechanical properties of RPC. However, there is no effect of adding waste glass powder in solving the spalling problem of RPC at high temperature up to 600˚C. This paper reports finding on the mechanical properties and high temperature performance of sustainable RPC that utilize waste glass powder in total replacement for the silica fume. This is carried out as an effort to address the high cost of the material used in the ordinary RPC and to enhance the recycling of local waste glass.

1. Introduction

Generally, reactive powder concrete (RPC) is regarded as an ultra-dense mixture of silica fume, water, Portland cement, fine quartz sand, superplasticizer, quartz powder, and steel fibers. However, at present, 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

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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 [1-3]. The high dosage of both Portland cement and silica fume in high performance concretes, does not only increases the cost, but also represents a significant drawback regarding sustainability due to the consumption of raw materials [4,5]. Therefore, RPC manufacturing needs to be designed based on economical material that produces high strength to weight ratio and high thermal resistance concrete [6].

Globally, 2.2 billion tons of solid wastes are expected to be generated annually by the year 2025 [7]. 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 [8]. 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 [9]. Study conducted by Kushartomo *et al.,* [10] showed that the maximum improvement in the mechanical performance can be achieved at 20 % replacement of waste powdered glass. Glass wastes with fly ash and ceramic waste had also been utilized to replace silica fume and sand in the RPC mixture design [11,12]. It is found that the full replacing of the silica fume by the combination, and replacing of 15 % sand by powdered ceramics waste is had shown promising improvement for the mechanical properties. Waste glass had also been incorporated into RPC design with a combination of fly ash, and slag as replacement for cement and silica fume [13]. In addition, hazard waste materials used as sand replacement in reactive powder concrete had resulted satisfactory properties of the recycled reactive powder concrete and enable safety encapsulation of the hazardous waste [14].

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 ℃, which often causes a devastating explosion [15]. This is due to its dense microstructure that is vulnerable to explosive spalling at elevated temperatures, and seriously jeopardizes the safety of RPC application [16-18]. 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 [19,20]. Therefore, this paper reports finding on the mechanical properties and high temperature performance of sustainable RPC that utilize waste glass powder in total replacement for the silica fume. This is carried out as an effort to address the high cost of the material used in the ordinary RPC and to enhance the recycling of local waste glass. The highlight of the study is on the assessment of the RPC at high temperature tested by direct burning at 600˚C.

2. Methodology

2.1 Materials

Materials used in this study consist of portland cement, fine aggregate, high range water reducing admixture, micro silica fume, waste glass, micro steel fiber and water.

2.1.1 Portland cement

Type I of the Ordinary Portland cement was used in all the performed experiments. Tables 1 and 2 list the collected results of the chemical analysis and the physical tests of the used kind of cement.

Table 1
The chemical composition of the cement

Chemical requirements	Testing method	Test results	Limitations
Sulfate content SO_3	IQ 472/1993	2.55	2.5 if $C_3A \leq 3.5$ 2.8 if $C_3A \geq 3.5$
Magnesium Oxide MgO	IQ 472/1993	1.78	≤5.0
Chloride Content	BS EN 196-2/2013	0.06	≤0.1

Table 2
Physical properties of cement

Properties	Testing Method	Test Results	Limitations
Setting time (Vicat's Method) Initial time (min)	BS EN 196-3/2016	153	≥ 45 min
Final time (hours)		3:39	≤ 10 hrs
Fineness (Blaine Method), m^2/kg	IQ 198/1990	398	Not specified
Soundness (expansion) Le Chatle	BS EN 196-3/2016	0.58	≤ 10
Compressive strength, MPa 2 day	BS EN 196-3/2016	25.2	≥ 20
28 day		52.4	≥ 40.5

2.1.2 Fine aggregate

A very fine aggregate of natural sand (with maximum size of 600 µm was used in this study. It was separated by sieving in a manner to satisfy the fine grading with the Iraqi Specifications No.45/1984. The used fine aggregate specific gravity, sulphate, absorption and chemical content were tested as and shown in Table 3.

Table 3
Grading of the Separated Fine Sand Compared with the Requirements of Iraqi Specification No.45/1984

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No.45/1984, zone 4
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.600	100	80-100
0.300	45	15-50
0.150	11	0-15

2.1.3 High range water reducing admixture (HRWRA)

The third generation super plasticizer was used to get mix with minimum water content and this admixture has significant effect on the present work. It represents aqueous solution of modified polycarboxylates which is known commercially as SikaViscocrete5930.

2.1.4 Micro silica fume (SF)

Silica fume (micro silica) is a consequence product collected during producing of the ferrosilicon alloys or silicon metal. Silicon dioxide (SiO_2) was initially formed in it as (non-crystalline) amorphous. The particles size was very small, about 100 times lesser than the middling cement particle. Silica fume is available as a densified powder or in a water-slurry form. It is generally used at 5 to 12% by mass of cementitious materials as a partial replacement for concrete structure that needs high strength or significantly reduced permeability to water (National Ready Mixed Concrete Association, 2000).

2.1.5 Micro steel fibers

Micro steel fibers were used throughout the experimental program. The properties of the used steel fibers are presented in Tables 4.

Table 4
Properties of micro steel fibers

Material	Low carbon steel wire, copper coated
Diameter	(0.2 - 0.25) mm
Length	(12 - 14) mm
Tensile strength	>2850 MPa

2.1.6 Waste glass powder

Table 5 explain the important physical and chemical properties of the waste glass powder used to replace silica fume in the reactive powder concrete mixing.

Table 5
Physical and chemical properties of waste glass powder

Physical Properties	
Specific gravity	2.5
Fineness	<75µm
Colour	White
Chemical properties (% by mass)	
Silica (SiO_2)	73
Alumina (Al_2O_3)	0.6
Iron oxide (Fe_2O_3)	0.3
Magnesium oxide (MgO)	1.8
Calcium oxide (CaO)	10.9
Sulphur trioxide (SO_3)	-
Sodium oxide (Na_2O)	14.2
Potassium oxide (K_2O)	0.1

2.2 Mix Design

Mix designs of the control RPC (control) and the sustainable RPC containing waste glass (M1) were listed in Table 6.

Table 6
Mix Design of control and sustainable reactive powder concrete

Mixes	Cement Kg/m^3	Sand Kg/m^3	Silica fume Kg/m^3	Waste glass powder Kg/m^3	Steel fiber %	Date palm fiber %	HRWR %	Water %
Control	880	970	220	0	2	0	5	0.175
M_1	880	970	0	220	2	0	5	0.175

2.3 Compressive Strength Test

To examine the behaviour of the control and sustainable RPC, the mechanical properties of reactive powder concrete were tested, and recorded at room temperature (20 °C).

2.3.1 Modulus of Rupture

The concrete modulus of rupture was determined by testing (50×50×300) mm^3 prism specimens in conformity with ASTM C 78-02. Each prism was simply supported and subjected to two points loading using ELE international machine with a capacity of (2000 kN) and the average results of these three prisms was taken. Eq. (1) was used to estimate the modulus of rupture.

$$fr = pl_s/bh^2 \qquad (1)$$

where:
fr: Modulus of rupture, (MPa)
P: Failure load, (N)
l_s: Span length, (mm)
b: Width of specimen, (mm)
h: Depth of specimen, (mm)

2.3.2 Splitting tensile strength

Splitting tensile strength has been determined by testing standard cylinders of (100×200) mm for every mix depending on ASTM C 496-04 specification using ELE international digital machine have a maximum capacity about (2000 KN/ 450000 lbf). The cylinders were cast, demoulded and cured in a similar way as for all specimens. The splitting tensile strength was calculated by using Eq. (2).

$$f_{sp} = 2p/\pi Dl \qquad (2)$$

where:
f_{sp}: Splitting tensile strength (MPa)
p: Maximum applied load in (N)
D: Diameter of cylinder (mm)
l: Length of cylinder (mm).

2.3.3 Modulus of elasticity

The modulus of elasticity of RPC was test using the ASTM C469 standard test method. Cylinders (100×200) for any temperature were prepared. The modulus of elasticity of Reactive Powder Concrete samples was calculated using Eq. (3).

$$E = (S_2 - S_1) / (\epsilon_2 - 0.000050) \quad (3)$$

where:
E = chord modulus of elasticity, (GPa)
S_2 = stress corresponding to 40 % of ultimate load (MPa)
S_1 = stress corresponding to a longitudinal strain, ϵ_1, of 50 millionths
ϵ_2= longitudinal strain produced by stress S_2.

2.4 Burning of Specimens

The specimens were burnt with direct fire flame a net of methane burners inside a stove with dimensions of (1500×1500×800mm) (length× width× height respectively). Real fire flame test was applied for the samples with maximum temperature equal to 600 ± 50 °C. For cooling regime, the fire flame was switched off at the end of the exposure time. The samples were removed immediately after being extinguished and picked by steel frame and allowed to be cooled outside the stove for a period ranging from (3 to 10 hrs).

3. Results

3.1 Density

The impact on RPC density of switching from silica fume to waste glass powder is depicted in Figure 1. With increasing curing age, both reactive powder concrete and sustainable reactive powder concrete showed an increase in density. The density of the control reactive powder concrete mix was 2.47 gm/cm^3 after three days, and the density increased by 0.40 % after seven days, and 0.81 % after 28 days. The density of M1 RPC mix was 2.42 gm/cm^3 after three days, and the density increased by 0.41 % and 0.83 % after seven and 28 days, respectively. This could be due to the fact that cement paste hydration is more complete as it matures.

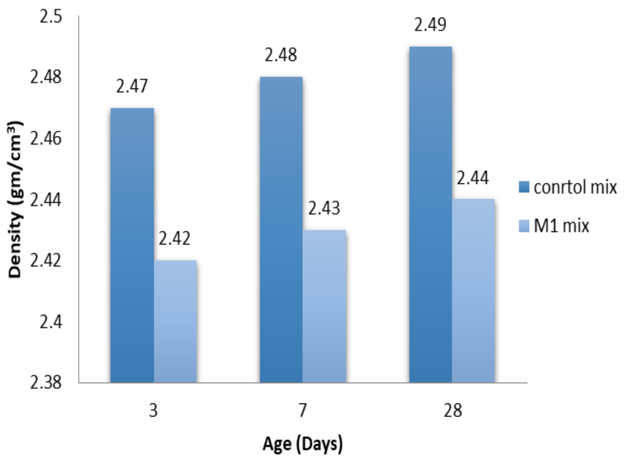

Fig. 1. Density of control RPC mix and M1 RPC mix

Inclusions of waste glass powder in reactive powder concrete as a replacement for silica fume, on the other hand, result in a drop in density for all ages. The density difference between the control mix and the M1 reactive powder concrete mix was 2.06 % after three days, 2.01 % after seven days, and 2 % after 28 days. The same behaviour in reactive powder concrete, with a density drop of 5.9 % following (20 % fly ash+ 80 % waste glass powder) substitution [1]. When silica fume is replaced by waste glass powder, the density of reactive powder concrete decreases. This reduction is most likely due to the waste glass powder's smallest particle size (less than 150 µm).

3.2 Colour

The colour of the finished sustainable reactive powder concrete (RPC) is somewhat altered when silica fume is swapped out for waste glass powder in the M1 sustainable reactive powder concrete mix. The control specimens of M1 mix are grey in colour, like the colour of silica fume, while waste glass powder is white in colour. The colour difference between the control mix and the M1 sustainable reactive powder concrete mix is due to the colour difference between silica fume and waste glass powder. Figure 2 shows that the M1 sustainable reactive powder concrete has a lighter colour than the control mix.

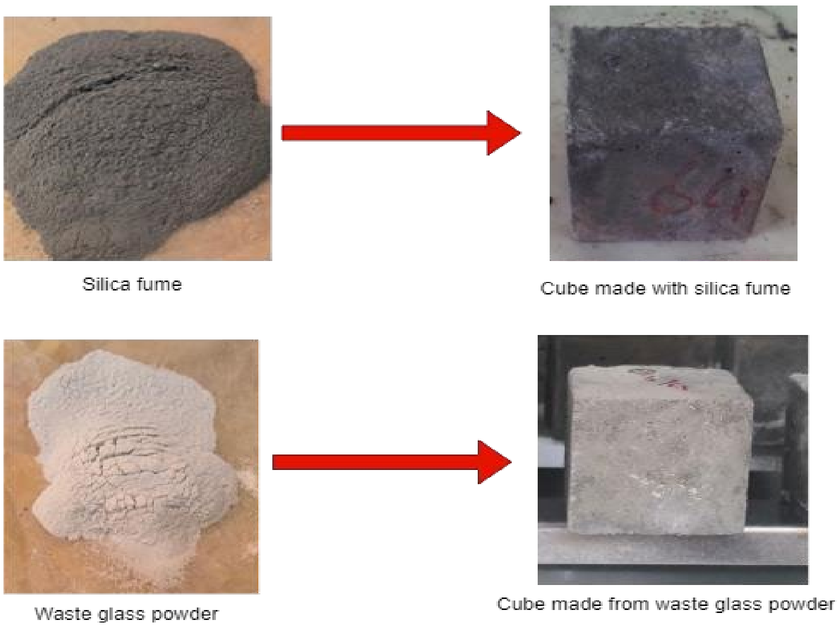

Fig. 2. Effect of waste glass powder on colour

3.3 Compressive Strength

The compressive strength of reactive powder concrete and M1 sustainable reactive powder concrete mixes at various curing ages is described in depth in this section. The compressive strength of control mix and M1 mix cubes is shown in Figure 3. To reduce the predicted error in any measured result, each value in this figure is the average of 3 cubic specimens.

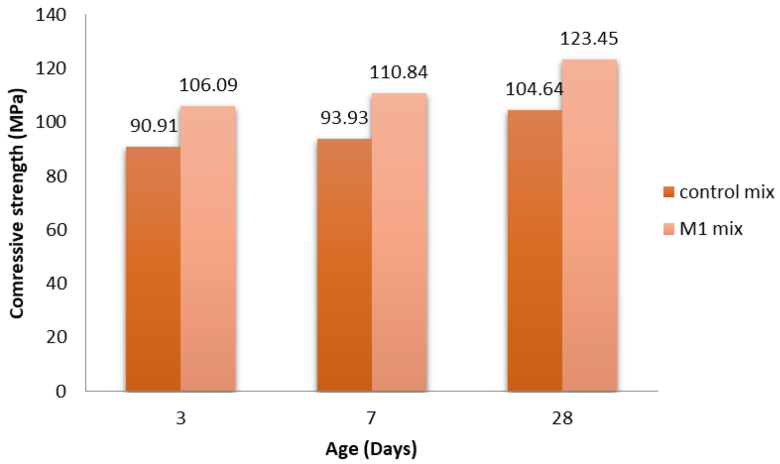

Fig. 3. Compressive strength of control RPC mix and M1 RPC mix

Both reactive powder concrete and M1 sustainable reactive powder concrete mix showed an increase in compressive strength with longer cure times. The control reactive powder concrete mix's compressive strength at three days was 90.91 MPa; at seven days, it increased by 3.32 %; and at 28 days, it increased by 15.10 %. The compressive strength of the M1 sustainable RPC mix was 106.09 MPa after three days, and it increased by 4.47 % after seven days and 16.36 % after 28 days, respectively. This is explained by the fact that when cement paste matures, its hydration becomes more complete, increasing the compressive strength of both control mix and M1 sustainable RPC mix.

On the other hand, the substitution of waste glass powder for silica fume in reactive powder concrete results in an increase in compressive strength for all ages. At three days the increment in compressive strength between control mix and M1 sustainable RPC mix was 16.69 % while the percentage at seven days was 18 present and at 28 days was 17.97 %. The same behaviour in reactive powder concrete was reported by Asteray *et al.*, [1] where the increase in compressive strength was 14.62 % after totally replacement for silica fume with (20% fly ash+ 80% waste glass powder). When rice husk ash is used in place of 30% of the silica fume the compressive strength also improves, with a 27.75 % rise [2]. Sui *et al.*, [5] also experienced an improvement in compressive strength of about 1.94% when calcium carbonate waste powder was used in place of 45% of the silica fume.

3.4 Splitting Tensile Strength

Both reactive powder concrete and M1 sustainable reactive powder concrete mix showed an increase in splitting tensile strength with longer cure times as seen in Figure 4. The control reactive powder concrete mix's splitting tensile strength at three days was 10.22 MPa; at seven days, it increased by 3.22 %; and at 28 days, it increased by 24.65 %. The splitting tensile strength of the M1 sustainable RPC mix was 11.8 MPa after three days, and it increased by 4.40 % and 16.18 % after seven days and after 28 days, respectively. This may be explained by the fact that when cement paste matures, its hydration becomes more complete, increasing the splitting tensile strength of both control mix and M1 sustainable RPC mix. On the other hand, the substitution of waste glass powder for silica fume in reactive powder concrete results in an increase in splitting tensile strength for all ages. At three days the increment in splitting tensile strength between control mix and M1 sustainable RPC mix was 15.45 % while the percentage at seven days was 16.77 % and at 28 days was 7.61 %.

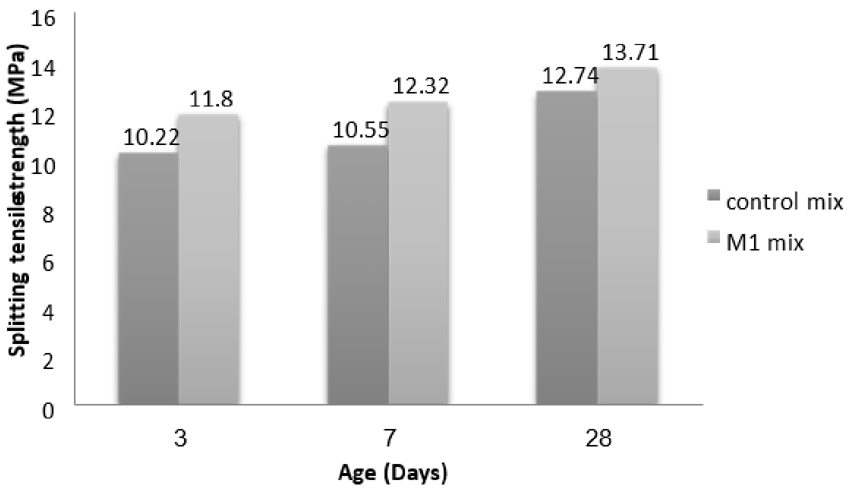

Fig. 4. Splitting tensile strength of control RPC mix and M1 RPC mix

3.5 Flexural Strength

Figure 5 compares the flexural strength of the M1 sustainable RPC mix and the control RPC mix. Both reactive powder concrete and M1 sustainable reactive powder concrete mix showed an increase in flexural strength with longer cure times. The control reactive powder concrete mix's flexural strength at three days was 28.02 MPa; at seven days, it increased by 3.10 %; and at 28 days, it increased by 14.45 %. The flexural strength of the M1 sustainable RPC mix was 32.28 MPa after three days, and it increased by 4.33 % and 15.83 % after seven days and after 28 days, respectively. This may be explained by the fact that when cement paste matures, its hydration becomes more complete, increasing the splitting tensile strength of both control mix and M1 sustainable RPC mix.

On the other hand, the substitution of waste glass powder for silica fume in reactive powder concrete results in an increase in flexural strength for all ages. At three days the increment in splitting tensile strength between control mix and M1 sustainable RPC mix was 15.20 % while the percentage at seven days was 16.58 % and at 28 days was 7.61 %.

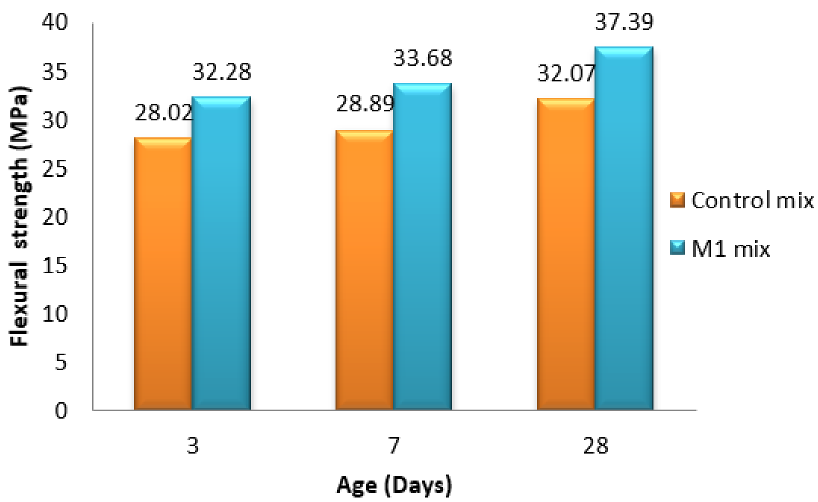

Fig. 5. Flexural strength of control RPC mix and M1 RPC mix

3.5 Modulus of Elasticity

The elastic modulus of reactive powder concrete for both original and sustainable reactive powder concrete is shown in Figure 6. Both reactive powder concrete and M1 sustainable reactive powder concrete mix showed an increase in modulus of elasticity with longer cure times. The control reactive powder concrete mix's modulus of elasticity at three days was 31.09 GPa; at seven days, it increased by 2.86 %; and at 28 days, it increased by 29.81 %. The modulus of elasticity of the M1 sustainable RPC mix was 35.32 GPa after three days, and it increased by 3.87 % and 14.26 % after seven days and after 28 days, respectively. This is explained by the fact that when cement paste matures, its hydration becomes more complete, increasing the modulus of elasticity of both control mix and M1 sustainable RPC mix. Also, the substitution of waste glass powder for silica fume in reactive powder concrete results in an increase in modulus of elasticity for all ages. At three days the increment in modulus of elasticity between control mix and M1 sustainable RPC mix was 13.60 % while the percentage at seven days was 14.73 % and at 28 days was 13.01 %.

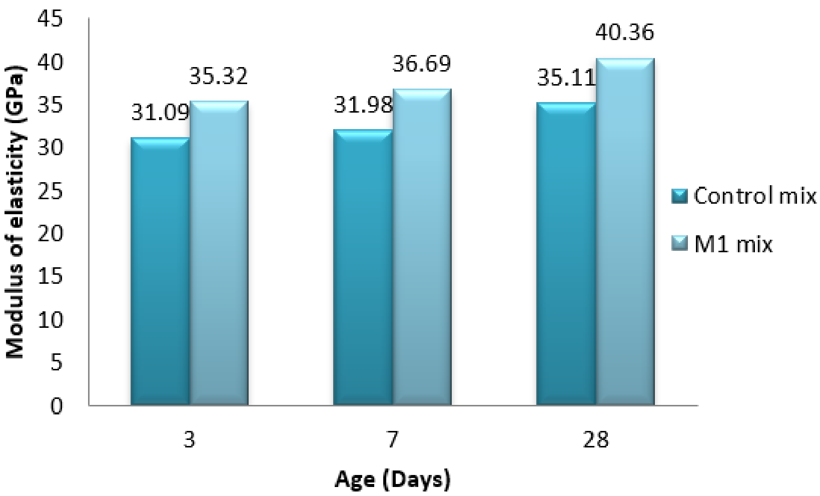

Fig. 6. Modulus of elasticity of control RPC mix and M1 RPC mix

3.6 High Temperature Performance

For a 30-minute period at high temperatures of 600 °C, fire tests were conducted using control and M1 sustainable reactive powder concrete mixtures had found that all of the M1 sustainable reactive powder concrete mix and control RPC mix spalled after being exposed to high temperatures as shown in Figure 7.

Internal cracks were the primary cause of spalling, according to the findings of fire tests and observations made on samples following tests that were collected for the specimens during and after exposure to real fire flame. Given that there is no obvious surface damage, partial or complete splitting of the surface layer from various depths beneath the specimen's core was suspicious. Before the breaking began, some part was pulled away from the surface. This raises the possibility that the spalling could be caused by the split layer buckling [21]. On the other hand, a rise in pore pressure might result in spalling [19]. In the M1 RPC mix design, waste glass powder completely replaced silica fume. On the spalling behaviour, the impact of utilizing waste glass powder as opposed to silica fume was investigated. According to the testing program, there is no impact on the spalling of RPC mix when employing waste glass powder. After exposure to high temperature more than 600 ℃, Control RPC mix and M1 RPC mix examine explosive spalling. Figure 8 illustrates the M1 RPC mix before and after exposure to fire test.

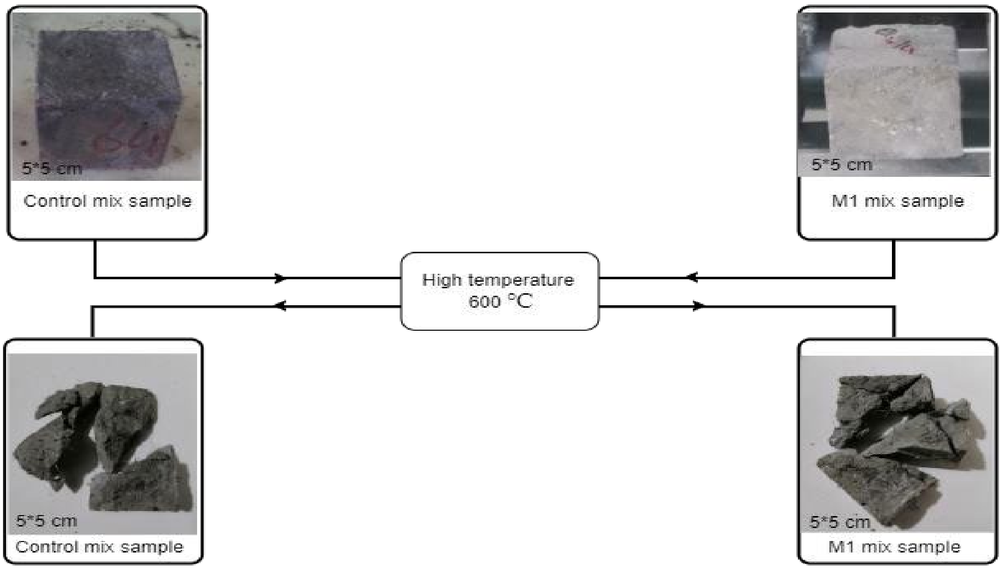

Fig. 7. Control mix and M1 mix after fire test

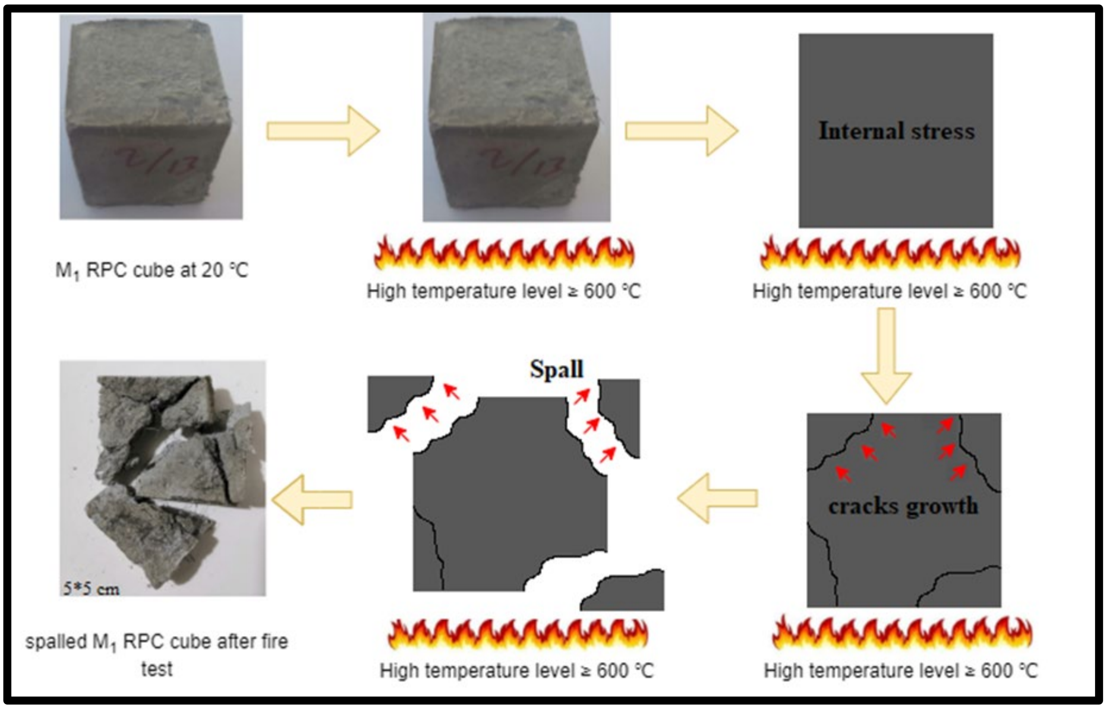

Fig. 8. Spalling mechanism of M1 RPC cube after exposure to fire test

4. Conclusions

The control reactive powder concrete mix has good physical and mechanical properties when it tests at normal temperature (before fire test). Adding waste glass powder to RPC instead of silica fume enhances in reducing the cost of RPC as well as reduces the pollution of environment due to waste materials. The control reactive powder concrete mix prone to explosive spalling after exposure to high temperature levels up to 600. RPC containing waste glass powder is lighter in colour than RPC made with silica fume. RPC containing waste glass powder changes the colour of RPC from darkish grey to light grey. Adding waste glass powder reduce the density of RPC by (0.05) gm/cm^3. Adding waste glass powder instead of silica fume improves the mechanical properties of RPC. There is no effect of adding waste glass powder in solving the spalling problem of RPC at high temperature levels up to 600˚C.

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