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Compressive and Flexural Strength of Recycled Reactive Powder Concrete Containing Finely Dispersed Local Wastes

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Abstract

The main objective of this experimental study is to investigate the behavior of Recycled Reactive Powder Concrete (RRPC) developed from finely dispersed local waste raw materials. In this study, RRPC was developed by utilizing local wastes (finely dispersed waste glass powder, waste fly ash and waste ceramic powder) together with Portland cement, fine sand, admixture, steel fibers and water through full replacement of silica fume as well as quartz powder for sustainable construction practice. In this study, all raw materials for making RRPC were analyzed for X-Ray Fluorescence analysis. For sustainability of local construction works, this study employed standard curing method at ambient temperatures instead of steam curing at higher temperatures. Moreover,, hand mixing was used throughout the study. To evaluate the structural performances of the developed RRPC mixes, compressive and flexural strengths of RRPC were investigated experimentally and compared with the control mix. The experimental results indicated that replacing the silica fume fully by finely dispersed local waste glass powder (GP) and fly ash (FA) is a promising approach for local structural construction applications. Accordingly, a mean compressive strength of 62.9 MPa and flexural strength of 8.8 MPa were developed using 50% GP-50% FA at 28th days standard curing. In this study, 17.56% larger compressive strength and 30.6% flexural strength improvements were observed as compared to the control mix.

Keywords

Local Wastes, Recycled Reactive Powder Concrete, Compressive Strength,

Flexural Strength, Standard Curing

1. Introduction

As a prime composite construction material in Civil Engineering, the rapid rise in the cost of concrete raw materials has led to serious environmental and economic effects. Waste disposal from different sources in Africa has continued to be a complex challenge for the society, both environmentally and economically. Currently, waste materials from different sources are already in utilization as a concrete ingredient to produce either in conventional or in high strength level.

However, in Africa, local wastes are not well utilized for structural concrete applications due to different limitations. First, due to urbanization of cities in Africa, there are vast amounts of construction related wastes. For these wastes, there is a lack of sustainable construction solutions to manage effectively and to reuse with operational technologies to save consumption of biomass resources and related rising of concrete raw material prices for local constructions. Secondly, it is also a challenge to produce high performance concrete for structural applications from locally produced waste materials since less costly components of conventional concrete are eliminated by more expensive elements (such as silica fume) to produce newly emerging concretes such as reactive powder concrete. Thirdly, few ingredients of high performance concrete such as quartz powder need high energy for preparation from quarry site till milling process.

In recent times, a new generation concrete called reactive powder concrete is under development as an ultra-dense mixture of water, Portland cement, silica fume, fine quartz sand, quartz powder, super-plasticizer and steel fibers [1]-[6]. It has been developed through microstructural engineering using very fine powders: sand, crushed quartz and silica fume with low water content [7] [8]. It is also indicated that reactive powder concrete is characterized by high doses of fine-grained cement and a low water-cement ratio [9], very high silica fume [10] and with the largest particle size as fine quartz sand with a particle size between 150 - 600 μm [11]. Compared to the conventional concrete, the particle size homogeneity, porosity, and microstructure properties were the primary improvements of RPC [12] [13] [14] [15].

Moreover, reactive powder concrete exhibits greatly ultra-high strength, improved durability and high toughness characteristics compared with traditional or even high performance concrete since it is prepared by eliminating all the coarse aggregates, using very low water to binder ratio by incorporating pozzolanic materials, very fine sand, steel fibers and by applying pressure and heat treatment [16] [17]. Higher strengths can be achieved after water curing at 90°C for 3 days [9]. The incorporation of silica fume in RPC matrix remarkably enhances the steel fiber-matrix bond characteristics [12]. As the main constituent of a typical reactive powder concrete, silica fume plays a significant role in improving both rheological and mechanical properties [18]. As the reactivity of pozzolana is quantified by measuring the amount of $Ca(OH)_2$ in the cement paste at different times, silica fume is much more reactive than fly ash or any other natural pozzolana [10]. However, it is noticed that high Silica fume content is one of the characteristics of Reactive Powder Concretes [19], which is uneconomical for local construction. The silica fume content in RPC is normally kept in the range of 25% - 30% of the cementitious material [1] in which this quantity within the mix may lead to uneconomical mix. Moreover, higher percentage of silica fume requires higher percentage of water, but as the water/cement ratio increases, the strength of RPC mix decreases [10]. However, higher percentages of silica fume lead to higher dosages of superplasticizer [18], which is also uneconomical. The development of Ultra High Performance Concrete (UHPC) in the concrete industry can be supported by the substitution of silica fume by another ultra-fine that lower cost, whose availability would not raise particular difficulties [20]. One of the best approaches to make concrete industries sustainable is the use of waste material in place of natural resources [21]. Additionally, to address the environmental concerns in the current situation, utilization of a supplementary cementitious material such as fly ash, or silica fume, or blast furnace slag, as raw material replacement is a value-added approach [22]. Nowadays, many industrial by-products have been standardized as supplementary cementing materials. Among these, fly ash was widely used as a supplementary cementitious material in concrete mixture mostly to replace cement [23].

In this study, to address the above limitations, desired local wastes were collected from construction sites and cement factories and proposed to develop RRPC. Locally available wastes such as waste glass powder and fly ash were proposed in this study to reduce the silica fume requirement and related cost.

Waste glass powder was used in many research projects for partial replacement of ingredients in concrete production [24]. Waste glass could be used in concrete in powder form to suppress the ASR tendency [2]. Due to finer particles, glass powder is more reactive than silica fume. Because of its high silica content, the use of waste glass powder as a supplementary cementitious material is commonly practiced. But, as per different scholars, its pozzolanic properties will be improved when it was ground finer than 75 um and up to 10% cement replacement in concrete yields similar results to fly ash at the same replacement level after 90-days [25]. Replacing silica fume in UHPC mix designs with fine glass powder could save the silica fume content, which is costly and in limited availability [26].

A number of studies have been studied on wastes to develop Reactive Powder

Concrete (RPC) by replacing silica fume. Among those studies, Zhn *et al.* (2016) [27] investigated usage of recycled powder produced from waste of clay bricks with cement solids to develop environmentally-friendly and cost-saving RPC by replacing silica fume at 20%, 40%, 60%, 80% and 100% by weight. Accordingly, the results showed that as the replacement rate of silica fume in RPC by recycled powder increased, the flexural strengths were tended to decrease.

It was also observed that RPC containing high volume ground granulated blast furnace slag (GGBFS) for replacement of silica fume has been producing a compressive strength of over 250 MPa after autoclaving which was a satisfactory mechanical performance. Additionally, the amount of silica fume was decreased with increasing amount of GGBFS [28]. On conventional concrete, flexural strength of fly ash plus glass powder decreases by 1% at 11% of glass powder percentage and thereafter it increases by 8% after 30% of increase in glass powder after 28 days [2].

In this study, finely dispersed waste glass powder, waste ceramic powder and waste fly ash were utilized for development of Recycled Reactive Powder Concrete (RRPC). The combination of finely dispersed waste glass powder and waste fly ash in three different percentages (at 80% - 20%, 50% - 50% and 25% - 75%) were utilized for full replacement of silica fume. The performance of developed RRPC was evaluated by compressive and flexural strength of RRPC.

2. Materials and Methods

2.1. Materials

In this study, Portland cement, fine sand, finely dispersed waste ceramic powder, finely dispersed waste glass powder, fly ash, steel fibers, superplasticiser and water available around Nairobi area were used for the development of RRPC mix and for the entire tests.

The cement used in this study were Portland cement Type I PowerPLUS 42.5 N Portland cement from Bamburi Cement Limited in Nairobi fulfilling the criteria for the European Norm Standard EN 197 Part 1: composition, specification and conformity criteria for common cements. Waste fly ash was also collected from Bamburi Cement Limited where special products are produced for commercial purposes.

For this study, fine sands obtained from Meru, Kenya and passing 600μm standard sieve size were used in all the mixtures and used in dry condition. The grading of fine sand, used for the entire mixtures, is shown in **Table 1**. Additionally, locally available waved wire steel fibers of 50 mm length with 0.22 mm thickness from Steel Wall Africa Nairobi branch were used for development of RRPC. Commercially available superplasticiser supplied by SIKA® Company Kenya Limited in Nairobi under the commercial name Sika Viscocrete-10 were used to attain workability. The ordinary drinking water was also used for preparation of the desired concrete mix following BS EN 1008:2002 [29]. Experimental results are presented comparatively with the control mix. To develop the control mix, MasterRoc MS 610 type densified Silica fume was used from BASF East Africa LTD in Nairobi. The technical data for silica fume was shown in Table 2.

Physical properties and particle size distribution of raw materials were determined based on British Standard 812-103.1:1985 [30]. The chemical compositions of all raw materials were characterized in Kenya Ministry of Mining using X-ray fluorescence (XRF) machine. The properties of raw materials used in this study were presented in Table 2, Table 3 and Table 4.

2.2. Methods

2.2.1. Finely Dispersed Waste Glass Powder and Ceramic Powder Preparation

For this study, waste ceramic and waste glass were collected from construction

Table 1. Fine sand grading.

Sieve No.	Cumulative % Retained	% Passing
4.75 mm	0.00	100.00
2.4 mm	0.00	100.00
1.2 mm	0.00	100.00
600 µm	0.00	100.00
300 µm	14.17	85.83
150 µm	91.13	8.87
75 µm	99.37	0.63

Table 2. Technical data for Silica fume.

Property	Description
Form	Powder
Color	Grey
Density	0.55 - 0.7 kg/l
Chloride Content	<0.1%

Table 3. Chemical composition of materials in this study.

Materials	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	Fe_2O_3	Loss of Ignition
Finely Dispersed Glass Powder	80	0.7	9.4	0.9	6	0.22	0.1	0.01	0.27	1.1
Fly Ash	52	20	7.3	0.7	6.3	1.6	1.14	0.04	6.4	2
Finely Dispersed Ceramic Powder	66	16.6	2.5	0.53	3.36	1	0.72	0.01	6.7	1
Fine Sand	67	12.6	2.94	0.6	2.7	2.5	1.24	0.11	8.7	0.8
Cement	18	4.7	60	0.6	0.4	0.51	0.53	0.01	4	2.63

Table 4. Properties of cement.

Parameter		Result
Specific Surface (cm^2/g)		3197
Water Demand (%)		25.65
Setting Time (Minutes)	Initial	160
	Final	252
Soundness (mm)		0.3
Compressive Strength (Mortar Prism) (N/mm^2)	At 2 days	19.3
	At 28 days	48.94

sites and crushed both through man power and crushing machine in Jomo Kenyatta University Engineering Workshop. Initially, the collected waste glasses and ceramics were crushed with a sludge hammer using manpower to make comfortable for the machine. Then, they were taken to the crushing machine to make them very fine and to produce pozzolanic powder. After getting finely grained powder products, the products were sieved through man powder using 150μm standard sieve to get finely dispersed glass powder and 300 μm standard sieve to get finely dispersed ceramic powder.

Finely dispersed ceramic powder was proposed as a sustainable as well as economically viable material to replace quartz powder. Moreover, after preparing 150 μm finely dispersed waste glass powder (GP) and collecting the waste fly ash (FA) from Bamburi Cement Limited in Nairobi, this study were proposed three mix proportions namely series 80% GP-20% FA, 50% GP-50% FA and 25% GP-75% FA to replace silica fume in full version.

2.2.2. Mix Design of RRPC Mixtures

For this study, RRPC was developed through preliminary tests based on the existing mix proportions of RPC by replacing the silica fume and quartz powder in full version by local waste materials [31]. On one side, finely dispersed waste glasses together with fly ash were proposed to replace silica fume fully. Additionally, quartz powder was replaced by finely dispersed local waste ceramic powder. Since the mix design was employed using this three local waste materials together with other core raw materials, the name "Recycled Reactive Powder Concrete" was given for the concrete mixture.

Moreover, to replace silica fume fully, waste fly ash and finely dispersed waste glass powder were composed at 20% - 80%, 50% - 50% and 75% - 25% of the full silica fume weight respectively in three series (Table 5). The control mix was developed from silica fume, Portland cement (42.5 N), finely dispersed waste ceramic powder, superplasticizer, fine sand, water and steel fibers. For all mixes, hand mixing, standard water curing and uniform water-binder ratio of 0.216 were used.

Hence, based on previous practices and preliminary laboratory works, the mix

Table 5. Mix proportions for 0.009 [M^3].

Materials	Mix Series			
	Control	Series 1	Series 2	Series 3
Cement (Kg)	7.58	7.58	7.58	7.58
Waste Ceramic Powder (kg)	1.52	1.52	1.52	1.52
Waste Glass Powder (kg)	0	1.52	0.95	0.47
Fly Ash (kg)	0	0.38	0.95	1.42
Fine Sand (kg)	8.34	8.34	8.34	8.34
Superplastcizer (kg)	0.23	0.23	0.23	0.23
Water (kg)	1.52	1.52	1.52	1.52
Steel Fibers (kg)	1.04	1.04	1.04	1.04
Silica Fume (kg)	1.89	0	0	0

proportions described in Table 5 were employed for development of RRPC and for evaluation of the entire tests.

2.2.3. Mixing Procedure, Specimen Preparation, Curing Procedure and Testing

For this study, watertight and non-absorbent 100 × 100 × 100 mm^3 cube, and 150 × 150 × 550 mm^3 prism moulds conforming BS EN 12390-1:2000 [32] were prepared. Then, RRPC specimens were prepared based on BS EN 12390-2:2000 [33], the methods for making and curing test specimens for strength tests.

In order to prepare specimens, dry mixing of ingredients was done for 3 minutes. After that, wet mixing was done by adding 80% of the water and all of superplasticicer into the mixed dry materials and was mixed for another 7 minutes. Then, the remaining water was added and mixing was done again until a visually acceptable mix was obtained. Hand mixing was employed throughout the entire specimen preparations.

After getting a uniform mix and placing layer by layer on moulds, compaction was employed in two layers by steel compacting rod of circular cross-section having 16 mm diameter and length 600 mm with rounded ends. Once leveling of the surface was made with steel floats, the specimens were leave in the moulds for one day till getting dry. After removal of specimens from the mould, the specimens were marked without damaging the specimen. Then, standard curing of the test specimens were done till testing days for 7, 14 and 28 days in water at a temperature of 20˚C ± 2˚C instead of steam curing at high temperature in conventional RPC.

For testing, before placing the test specimens centrally in the testing machine, any excess moisture from the surface of the specimen were wiped. Then, three specimens were tested for the mechanical properties of RRPC as per the British Standard testing procedure for hardened concrete. The compressive strength was tested by automatically controlled universal testing machine at constant rate of loading (rate of 0.500 KN/Sec and start load of 0.250 KN with 15% stopping load) at the age of 7, 14 and 28 days of standard water curing and the average values were reported. Additionally, the flexural strength was determined as per Figure 1 below after 28 days of standard water curing. For testing the flexural strength, two supporting steel rollers and two upper rollers were used for applying loads in the universal testing machine. The load arrangement were two-point loading conforming BS EN 12390-5:2000 arranged with an upper span of 150 mm and lower span of 450 mm at a constant load rate of 0.150 MPa/Sec and start load of 0.100 KN with 15% stopping load.

3. Results and Discussion

3.1. Pozzolanic Properties of Local Waste Raw Materials

The results of the chemical analysis for local waste materials proposed in this study were compared with the minimum requirement for a standard pozzolana quality as per ASTM C618. The overall chemical composition of a pozzolan is considered as one of the parameters governing long-term performance (e.g. compressive strength) of the blended cement binder, ASTM C618 prescribes that a pozzolan should contain $SiO_2 + Al_2O_3 + Fe_2O_3 > 70$ wt%.

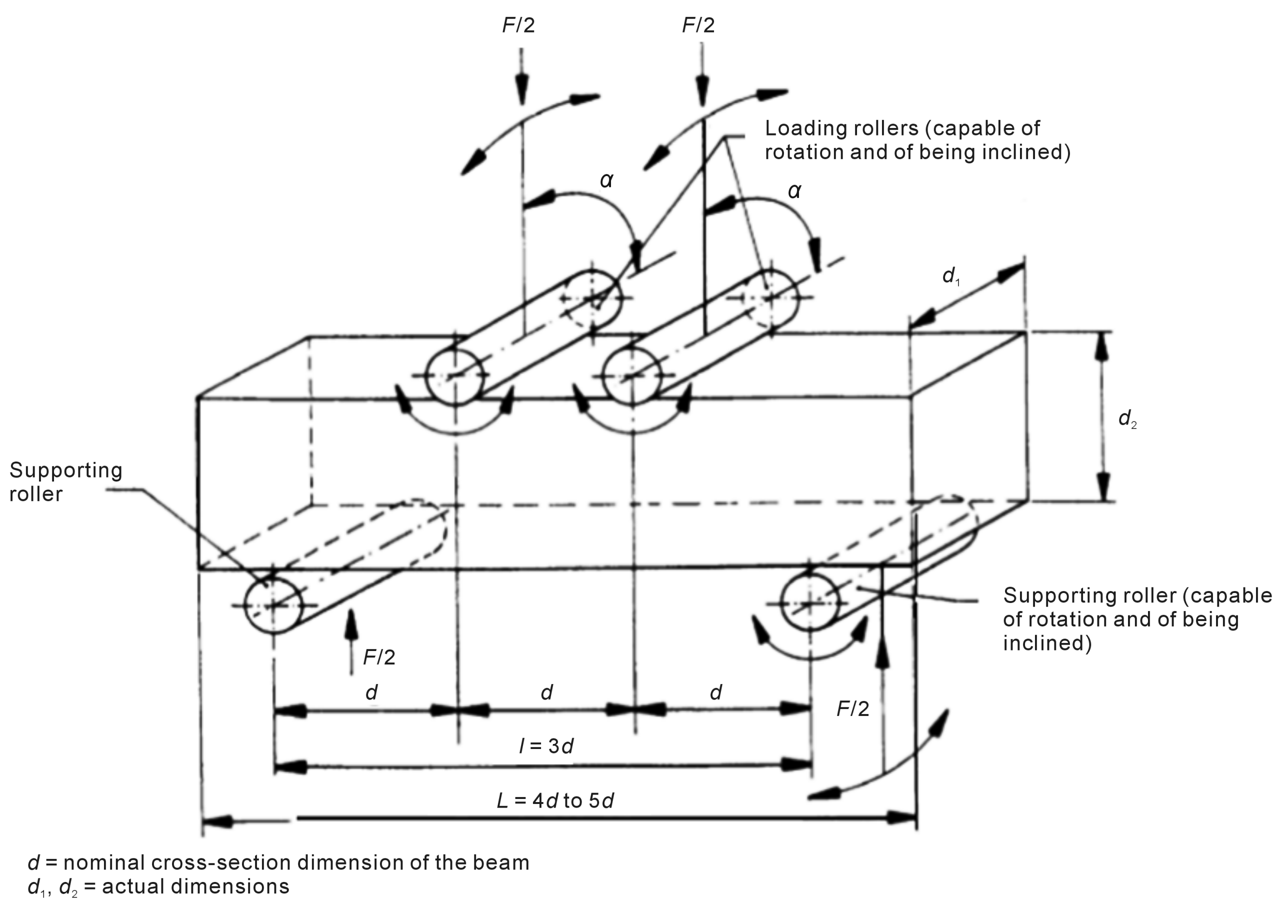

Figure 1. Arrangement of two-point loading of test specimen (Source: BS EN 12390-5:2000).

Figure 2 shows the chemical compositions (silica, alumina and iron oxide content) of selected local wastes in this study after XRF analysis. As evaluation criteria, the sum of the three mineral components (silica, alumina and iron oxide content) in each local waste should be compared with the requirement of ASTM C618 as a pozzolan.

Accordingly, finely dispersed glass powder contains 80.97%; fly ash contains 78.4% and finely dispersed ceramic powder contains 89.3% by weight. Since their chemical compositions are greater than 70 (by weight %), they fulfill the requirement and hence, the local waste materials used in this study were revealed a wonderful pozzolanic property that can greatly affect the long-term performance of RRPC product.

3.2. Compressive Strength of RRPC

One of the desires to identify the mechanical performance of the produced RRPC in this study was compressive strength evaluated by replacing different percentages of the proposed materials. The mean compressive strengths of three RRPC specimens produced from four categories (including control mix) were presented in Figure 3.

The first series of RRPC mix were developed by replacing the silica fume fully using 20% fly ash (FA) and 80% finely dispersed glass powder (GP). A maximum mean compressive strength of 59.41 MPa were observed after 28 days standard curing.

On the other hand, in the second series of RRPC mix, 50% fly ash (FA) and 50% finely dispersed glass powder (GP) were employed to replace the silica fume fully. As shown in Figure 3, 14.25% and 5.36% rise in compressive strengths were observed after 14th and 28th days standard curing respectively compared to the early observed value after the 7th days standard curing. Similarly, 3.31% and 14.53% rise of compressive strength was observed in the third series of RRPC mix that comprises 75% fly ash (FA) and 25% finely dispersed glass powder (GP) to replace silica fume fully.

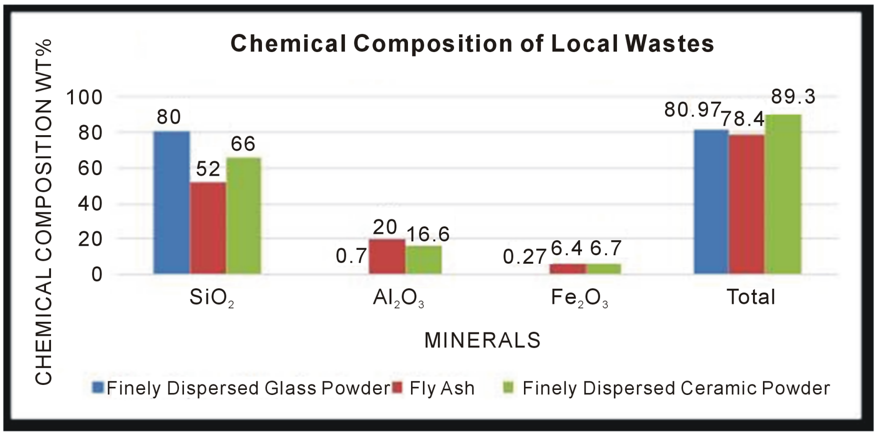

Figure 2. Chemical composition of waste materials in the study.

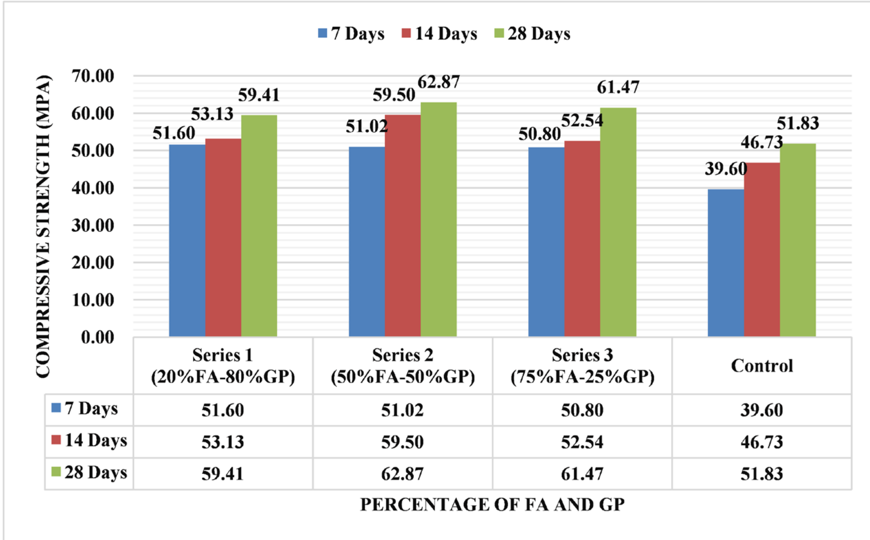

Figure 3. Compressive Strength of RRPC containing of FA and GP at different curing ages.

3.3. Flexural Strength of RRPC

Figure 4 shows the flexural strength of RRPC beams with different percentages of fly ash and finely dispersed glass powder. In **Figure 5**, test arrangements and testing for flexural strength of beam in the laboratory was observed. From **Figure 4**, a maximum flexural strength 8.836 MPa was observed using series 2 mix proportion. Compared to the mix control, 30.58% was improved using the series.

Like this study, many studies were done on conventional and high performance concrete by using waste glass powder and fly ash mostly to replace the cement and few studies to replace the silica fume content.

As per H. Du and K. H. Tan (2017), the application of recycled glass in conventional concrete as supplementary cementitious material to a much larger amount, up to 60% was seen and exhibits better mechanical behaviors, and more distinctly by the higher durability performance beside the lower amount of raw materials, waste disposal, energy consumptions and carbon footprint [22]. On the other hand, I. Dumitru *et al.* (2010) were carried out to assess the potential of the crushed recycled glass using sand and cement replacement of waste glass and it was observed that with the incorporation of 45% of crushed glass as a natural sand replacement, the compressive and flexural strengths have marginally increased, but as a cement replacement powder glass showed lower compressive strength and marginally higher drying shrinkage than the control mix [34]. E. Ghafari *et al.* (2016) also evaluated the ability of supplementary cementitious materials, such as fly ash and ground granulated blast furnace slag, on autogenous shrinkage of ultra-high performance concrete to be used as replacement of silica fume. It was also concluded that the incorporation of fly ash and ground granulated blast furnace slag gives similar performance in compressive strength

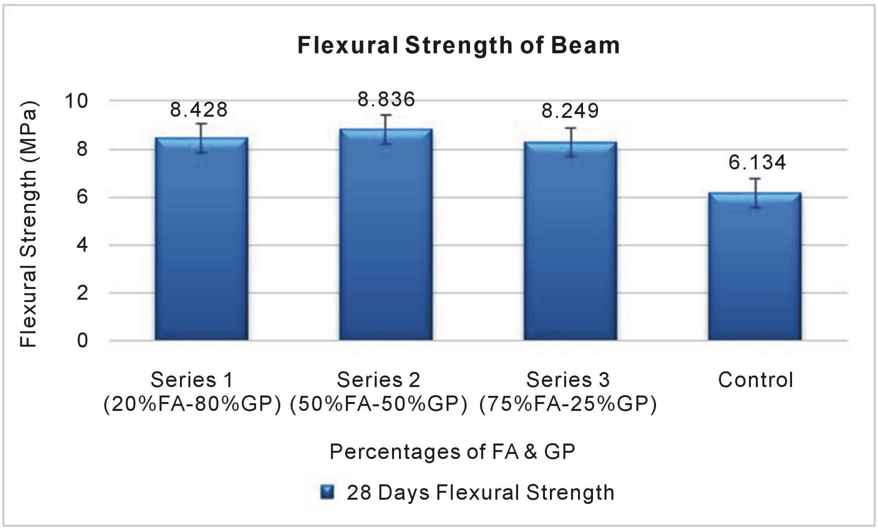

Figure 4. Flexural Strength of RRPC Beam containing of FA and GP at 28 days curing ages.

Figure 5. Flexural strength test in the laboratory.

when compared to the reference mixture which contains silica fume. In particular this study was observed that although incorporating fly ash into the mixtures results in a slight decrease of the mechanical properties [18]. N. A. Soliman (2017) also developed a sustainable UHPC by using fine glass powder to replace silica fume, in which 30% fine glass powder can be recommended for compressive-strength development for an optimum replacement of silica fume since it exhibits 15% higher strength after 2 days of hot curing compared to the concrete mix with silica fume [26]. Moreover, S. C. Kou and F. Xing (2012) were examined the effect of reject fly ash and recycled glass powder as replacement materials for the silica sand and cement respectively used to prepare ultrahigh performance fiber-reinforced concrete at 25˚C and 90˚C to determine differences in mechanical properties. The results showed that using reject fly ash and recycled glass powder reduces the flow ability of fresh concrete and the use of GP increased the mechanical properties [35].

Accordingly, unlike the above studies that uses waste glass powder and fly ash individually to replace either cement or silica fume, in this study the combined effect was evaluated for full replacement of silica fume in RRPC development. The experimental results indicated that a mean compressive strength of 62.9 MPa and flexural strength of 8.8 MPa were developed using 50% GP-50% FA at 28^{th} days standard curing.

4. Conclusions

In this study, Recycled Reactive Powder Concrete (RRPC) from local wastes at standard curing was developed and mechanical properties were investigated experimentally. Based on the experimental results, the following conclusions can be drawn:

1) The local waste materials used in this study were revealed a wonderful pozzolanic property that can greatly affect the long-term performance of RRPC product.

2) In all mix proportion series, higher early mechanical strength was observed and increased with curing age.

3) The optimal FA-GP content in most mix proportion series for getting higher mechanical strength is by replacing silica fume fully which is 50% FA-50% GP.

4) A maximum mean compressive strength of 62.87 MPa at 28th days curing age can be produced using 50% fly ash (FA) and 50% finely dispersed glass powder (GP) combinations. Compared to the control mix, 17.56% larger compressive strength can be achieved using 50FA-50GP Mix series.

5) A maximum flexural strength 8.836 MPa was observed using 50% fly ash (FA) and 50% finely dispersed glass powder (GP) combinations, which has 30.58% improvement compared to the mix control.

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