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Mechanical and microstructural properties of recycled reactive powder concrete containing waste glass powder and fly ash at standard curing

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Abstract: The objective of this study is to develop recycled reactive powder concrete from local waste raw materials and investigate their combined effect on mechanical properties for sustainable construction. Waste glass powder from construction sites and waste fly ash from cement industries in three different percentages were utilized for full replacement of silica fume. Waste ceramic powder was also utilized to replace quartz powder fully. Recycled reactive powder concrete were developed from Portland cement, finely dispersed waste glass powder, waste ceramic powder, waste fly ash, fine sand, admixture, steel fibres and water at standard curing and using hand mixing. All raw materials were analyzed for X-Ray Fluorescence analysis. To evaluate the mechanical performances of the developed concrete, compressive and flexural strengths were investigated experimentally and compared with the control mix. The experimental results indicated that replacing the silica fume fully

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PUBLIC INTEREST STATEMENT

In the construction industry, utilization of local wastes is an important issue to safeguard the environment and solving economic problems of raw materials, besides conserving the existing natural resources. Due to the vast amount of local wastes, the intention of this study is to utilize the identified wastes for recycled reactive powder concrete in the assembly of civil engineering structures to reduce the cost of raw material and to save the entire environment. Initially, local wastes were taken from their source; crushed in a finely dispersed way and sieved with standard sieves. After material characterization, recycled reactive powder concrete was developed, casted and tested for different experiments. Accordingly, developing recycled reactive powder concrete containing local wastes at standard curing makes strategic to use it in local constructions for structural works. Consequently, this study is vital and its final outcomes were advantageous in concrete technology, waste management and environmental engineering streams.

by finely dispersed local waste glass powder and fly ash is a promising approach for local structural construction applications. A mean compressive strength of 62.9MPa and flexural strength of 8.8MPa were developed using 50% glass powder 50% fly ash 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.

Subjects: Engineering Education; Materials Science; Clean Tech; Civil, Environmental and Geotechnical Engineering

Keywords: local wastes; recycled reactive powder concrete; mechanical properties; standard curing

1. Introduction

Today, global warming and environmental devastation have become manifest harms, concern about environmental issues, and a changeover from the mass-waste, mass consumption, mass-production society of the past to a zero-emanation society is now viewed as significant (Sawant & Kandekar, 2016).

The issue of sustainability is taken as the logic driving concept for the next phase of radical materials innovation. Sustainable construction has received much attention throughout the world over the last few years (Yeheyis, Hewage, Alam, Eskicioglu, & Sadiq, 2013).

In concrete production, sustainability can be achieved by innovations in substitutions of material used. Cement-based materials are the most abundant materials in the world. Due to the high demand of natural resources, engineers have growing interests in sustainable development by choosing sustainable material for eco-friendly construction & to save the environment by utilizing waste products generated by industries (Anwar, Ahmad, Husain, & Aqeel, 2015).

Hence, the use of locally available materials as well as the use of industrial and agricultural waste in the building industry has become a potential solution to the economic and environmental problems of particularly developing countries (Le, Nguyen, & Ludwig, 2014).

High demand of natural resources due to rapid urbanization and the disposal problem of agricultural wastes in developed countries have created opportunities for use of agro-waste in the construction industry. Many agricultural waste materials are already used in concrete as replacement alternatives (Prusty, Patro, & Basarkar, 2016). When compared to the use of primary natural resources, the valorization of industrial wastes and their up-grading to alternative raw materials can present several advantages (Andreola, Barbieri, Lancellotti, Leonelli, & Manfredini, 2016) for sustainable ways of construction.

However, 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 (Ghafari, Costa, & Júlio, 2015). Reuse of agricultural wastes and industrial by-products for building materials has been gaining popularity in the recent years (Ling & Teo, 2013).

Nowadays, sustainable waste management is an ongoing trend worldwide accomplished through utilization of recycled waste products in the construction industry (Ali, El-Dieb, Aboubakr, & Taha, 2016). Moreover, ecological balance of nature can be kept by usage of diverse raw materials. It was described that, 30–40% waste materials produced from forest products and agriculture materials can be recycled for functional product (Asim et al., 2015).

In the scientific community, the development of innovative materials and methods aiming at extending the life-time of both existing and new structures is mandatory for the sustainability of the construction sector. According to Ghafari et al. (2015), the partial replacement of silica fume and Portland cement by incorporating supplementary cementing materials (SCMs) can be practical to produce UHPC with equivalent mechanical performance.

Many industrial by-products like silica fume have been standardized as SCMs. However, these traditional SCMs are not always available in all regions and would be costly to transport. Hence, developing local alternative SCMs is of paramount importance (Omran & Tagnit-Hamou, 2016). Additionally, since shortage of post-consumer disposal waste sites were one of the principal problems in most developing countries, regenerating and using waste product as a resource and prevent environmental pollution is the best mechanism (Vasudevan, 2013).

Moreover, these days, a new generation concrete called reactive powder concrete is under development as an ultra-dense mixture of silica fume, water, Portland cement, fine quartz sand, superplasticizer, quartz powder, and steel fibers. Compared to conventional and high performance concretes, reactive powder concrete mixtures provide better properties since they are optimized at micro-scale level (Ahmad, Zubair, & Maslehuddin, 2015). On the other aspect, for environmental sustainability and enhancement of concrete properties, waste materials such as construction and demolition wastes and organic wastes have been introduced in the making of concrete (Zimbili, Salim, & Ndambuki, 2014).

In this regard, to solve raw material shortage, a culture of using local waste raw materials in the African construction sector should be adopted in the construction sector (Asteray, Oyawa, & Shitote, 2017). Keeping in view about the environmental pollution which may leads to some serious issues of health, it is essential to use locally available pozolanic materials (Khan & Khan, 2017).

Projections are that between 2000 and 2050, world population will grow 50%, global economic activity will grow 500%, and global energy and materials use will grow 300%. Commenting on the effects of material resource use on the environment, the heads of major research institutes in the United States, Germany, Japan, Austria, and the Netherlands have noted that unless economic growth can be dramatically decoupled from resource use and waste generation, environmental pressures will increase rapidly (Matthews et al., 2000).

Accordingly, the following issues were identified as a rational for this study.

First and foremost, compared to other construction materials, concrete is the most versatile and prime composite construction material all over the world by using different ingredients. In this regard, next to water, concrete is the second most used substance on earth which consumes a significant amount of raw materials. This rapid rise in concrete raw material use has led to serious environmental effects such as economical unbalances, resource shortage, biodiversity loss, habitat destruction, and desertification.

Secondly, it is also a challenge to produce high performance concrete for structural applications from local materials since least costly components of conventional concrete are eliminated by more expensive elements which includes silica fume, quartz sand and quartz powder to produce newly emerging concretes like reactive powder concrete. Concrete production from these materials is facing additional raw material expenses and time during the import process for local constructions. As per the report on Emerging Construction Technologies (ECT) team, the mineral component optimization alone in Reactive Powder Concrete results in a substantial increase in cost over and above that of conventional concrete (Purdue-ECT-Team, 2007). Additionally, it was also articulated that energy-consuming of the heat curing and the milling of quartz sand were lead application scarceness of Reactive Powder Concrete (Gu, Ye, & Sun, 2015). Generally, the common RPC is more expensive than traditional materials for special technologies applied in preparation procedures and with high content of expensive materials in preparation. For example, coarse aggregates were removed and replaced with graded quartz sands (Tang, Xie, & Long, 2016). Moreover, silica fume is one of the main constituents of reactive powder concrete in which its dosage is normally kept in the range of 25–30% of the cementitious material. Reactive Powder Concretes are characterized by high silica fume content (Cheyrezy, Maret, & Frouin, 1995). Beside its availability problem, usage of silica fume affects the concrete production costs, even if it gives a strong matrix. Beyond the cost problem, silica fume concrete shrinkage rate is large, workability is poor influencing the smoothness of concrete quality and it is easy to produce temperature cracks. Hence, replacing main ingredients with finely dispersed local wastes seems to be a feasible solution to solve economic and ecological related issues as well as to produce viable recycled reactive powder concrete.

Thirdly, waste disposal from different sources (industrial, agricultural areas, mining, households) has continued to be a complex challenge for the society in Africa, both environmentally and economically. Unless the society recycles these wastes by changing them into functional products, the inappropriate disposal may lead to contamination of resources and may create greenhouse gasses that contribute to global warming.

Fourthly, at this time, there is a growing market potential for sustainable materials and design concepts, which in turn encourages development in materials processing. To make sustainable materials and material systems cost competitive and environmentally friendly with existing products on the market, it requires a radical technological breakthrough in how materials are developed that makes them as cheap to produce as traditional alternatives. This can be solved by the current waste-based concrete technology.

Therefore, to fulfill the above gaps, recycled reactive powder concrete from finely dispersed local wastes were developed in this study as a proper construction material in the emerging concrete technology for future Civil Engineering projects.

2. Background and existing practice for reactive powder concrete

Within the last decades in civil engineering materials stream, high strength and high performance ingredients have an increasing trend in structural applications (Yiğiter, Aydın, Yazıcı, & Yardımcı, 2012). Presently, researches on concrete have revealed for attaining higher performances (Feylessoufi et al., 1996) to achieve High strength concrete (HSC). HSC is defined as a concrete that has higher durability and strength (Hakim, Noorzaei, Jaafar, Jameel, & Mohammadhassani, 2011) that meets special combination of uniformity and performance requirements as compared to the conventional concrete that cannot be achieved routinely using conventional ingredients, mixing, placing as well as curing procedures (Öztaş et al., 2006). Due to significant advances in technological applications, high-performance concrete (HPC) is superior to conventional concrete in terms of density and micro-structure via a refined mixing scheme (Tai, Pan, & Kung, 2011).

Moreover, ultra-high performance concrete (UHPC) has become a new focus for researchers and the concrete industry since it is characterized by high compressive strength and excellent durability properties.

These days, the most widely used UHPC is the so-called Reactive Powder Concrete (RPC) and its derivatives (Cwirzen, Penttala, & Vornanen, 2008). It became a focus of concern as an alternative to conventional concrete and even steel (Zhou & Hu, 2015) that has been widely used in engineering practice as a new kind of structural material (An, Zhang, & Yi, 2008). To improve the strength, serviceability, and safety of UHPC, nanotechnology principles were applied. Furthermore, for cost reduction and structural aesthetic enhancement, improvements in the compressive strength have allowed concrete structural member size and self-weight to be significantly reduced. Ultra- high strength concrete (UHSC) and reactive powder concrete (RPC) were among many UHPCs currently available on the market (Yi, Kim, Han, Cho, & Lee, 2012).

Reactive powder concrete (RPC) is first developed in France as a new type of ultrahigh strength concrete to offer mechanical and durability related advantages from crushed quartz (excluding the coarse aggregate), cement, quartz powder, silica fume, superplasticizer, and steel fiber. Its application has been increasing for works that need high class of concrete such as in bridge and military engineering works (Ji, Chen, & Zhuang, 2012; Long, Shi, Ma, & Xie, 2016). RPC is made from fine matrix with short steel fibres (Bayard & Plé, 2003) and is characterized by high doses of fine-grained cement and a low water–cement ratio (Canbaz, 2014). As compared to ordinary cement-based materials, the primary improvements of RPC include the particle size homogeneity, porosity, and microstructures (Chan & Chu, 2004). As per Cheyrezy et al. (1995), RPC is characterized by high silica fume content and very low water to cement ratio.

Rahman, Molyneaux, and Patnaikuni (2005) also explained that Reactive Powder Concrete is developed by the combined effort of three companies namely Bouygues, Lafarge and Rhodia working in France with 170–230 MPa compressive strength and 25–60 MPa flexural strength using steel fibres, highly durable and aesthetically pleasant appearance.

The mixture proportions used for the trial mixtures of this study were prepared based on previous researches done by different scholars on reactive powder concrete. Based on previous mix designs, trials were tested for optimization purpose.

Ahmad et al. (2015) were studied the effect of water/binder ratio (0.15, 0.175, and 0.20), cement content (1,000, 1,100, and 1,200 kg/m^3) and silica fume content (15, 20, and 25% of cement). Moreover, corresponding to an optimal dosage of 6.2% of the mass of fresh RPC, 157 kg/m^3 steel fiber content were utilized in all the mixtures. From the above proposed variables, 138.9 MPa maximum compressive strength were observed at 28 days using the mix proportion indicated in Table 1.

According to Richard & Cheyrezy (1995), two types of concretes: RPC 200 and RPC 800 were recommended by varying steel fibers and aggregates as described in Table 2.

Table 1. Mix proportion of RPC by Ahmad et al. (2015)

Cement (kg)	W/B ratio	Sand (kg)	Silica fume (kg)	Steel fiber (kg)	Superplastcizer (kg)	Water (kg)
1,100	0.15	652.09	275	157	48.81	206.25

Table 2. Mix proportions of RPC by Richard and Cheyrezy (1995)

	RPC 200		RPC 800	
	Fibered		Silica aggregates	Steel aggregates
Portland cement	1	1	1	1
Silica fume	0.25	0.23	0.23	0.23
Sand 150–600um	1.1	1.1	1.1	1.1
Crushed quartz d50 = 10um	–	0.39	0.39	0.39
Superplasticizer (Polyacrylate)	0.016	0.019	0.019	0.019
Steel Fiber *L* = 12 mm	0.175	0.175	–	–
Steel Fiber *L* = 3 mm	–	–	0.63	0.63
Steel aggregates < 800 um	–	–	–	1.49
Water	0.17	0.19	0.19	0.19

Moreover, So, Jang, Khulgadai, and So (2015) manufactured modified RPC using a combination of ternary pozzolanic materials including silica fume, blast furnace slag, and fly ash as per the mix design shown in Table 3. Among the modified RPC specimens, the BS10FA30 mixture (blast furnace slag 10% and fly ash 30% by weight of cement) showed excellent mechanical performance under high temperatures. The residual compressive, flexural, and splitting tensile strengths of the specimen after exposure to 1,000°C were 68, 8, and 5 MPa, respectively, which indicates 36, 22, and 29% of the original strength at 20°C.

Kushartomo, Bali, and Sulaiman (2015) also developed RPC by varying glass powder content at 10, 20 and 30% of cement to substitute quartz powder using steam curing at 95°C. Accordingly, 136 MPa compressive strength, 17.8 MPa split tensile strength and 23.2 MPa flexural strength maximum average values were observed using 20% glass powder substitute after 14 days as per the mix proportion in Table 4 for volume of 0.023 m^3.

Aïtcin, Lachemi, Adeline, and Richard (1998) also developed RPC as per the mix design stated in Table 5 for a compressive strength of 180 MPa, direct tensile strength of 7 MPa and flexural strength of 40 MPa.

In general, by referring different scholars, Ahmad et al. (2015) summarizes the following recommendations for RPC making materials:

(1) The silica fume content is kept in the range of 25–30% of the cementitious material.
(2) For enhancing the homogeneity, coarse aggregate is replaced by fine quartz sand. The maximum size of sand is recommended to be 600 μm about 41% by weight.
(3) Crushed crystalline quartz powder in the size range of 10–15 μm is used as a filler.
(4) Superplasticizer is needed to achieve its required flowability.
(5) Steel fibers with optimum dosage of 6.2% (by weight of RPC) should be utilized.

Table 3. Mix proportions of modified RPC by So et al. (2015)

Material	SF25	B30F10	B10F30
Cement (kg/m^3)	868	766	752
Silica fume (kg/m^3)	217	192	188
Blast furnace slag (kg/m^3)	–	230	75
Fly ash (kg/m^3)	–	77	226
0.3–0.5 mm Quartz (kg/m^3)	582	504	513
0.15–0.3 mm Quartz (kg/m^3)	174	153	150
0–45 um Quartz powder (kg/m^3)	174	153	150
Steel fibers (kg/m^3)	240	240	240
Poly propylene fiber (kg/m^3)	8	8	8
Superplasticizer (kg/m^3)	52	46	45
Water (kg/m^3)	165	146	143
Water/binder ratio	0.19	0.14	0.14

Table 4. Mix proportion of RPC by Kushartomo et al. (2015)

Cement	Silica sand	Silica fume	Superplastcizer	Glass powder	Steel fiber	Water
19.365	21.301	4.841	0.581	3.873	2.665	3.873

Table 5. Composition of the RPC by Aïtcin et al. (1998)

Material	Cement	Silica fume	Crush Quartz	Sand	Superplastcizer	Steel fiber	Water
Quantity (kg/m$^{3)}$	705	230	210	1,010	37.5	190	195

For this study, recycled reactive powder concrete were developed based on the above referenced mix designs and preliminary laboratory investigations from Portland cement, finely dispersed local wastes as a pozolanic source material by replacing silica fume, finely dispersed waste ceramic powder replacing quartz powder, superplasticizer, fine sand, water and steel fibres.

3. Research methodology

For this study, experimental design was employed as a research design. As an innovative construction raw material, a proof of viable local wastes were selected as a criterion for fulfilling sustainability issues for development of Recycled Reactive Powder Concrete. Accordingly, raw materials, experimental details and data analysis methods were discussed as follows.

3.1. Materials

In this study, Portland cement, silica fume, 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.

More specifically, the raw materials used in this study were described as follows.

3.1.1. Portland cement

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. The properties of cement used in this study were shown in Table 6.

Table 6. Properties of Portland cement used in this study

Parameters	Specific surface (cm^2/g)	Water demand (%)	Setting time (Minutes)		Soundness (mm)	Compressive strength (Mortar Prism) (N/mm^2)	
			Initial	Final		At 2 days	At 28 days
Results	3,197	25.65	160	252	0.3	19.3	48.94

Table 7. Grading of fine sand for this study

Sieve No	Cumulative % Retained	% Passing
600 um	0.00	100.00
300 um	14.17	85.83
150 um	91.13	8.87
75 um	99.37	0.63

3.1.2. Silica fume
Silica fume, also known as microsilica, is a by-product of the production of silicon and silicon alloys in electric arc furnaces which is added to cement to produce high performance concretes. Even if it is not easy to obtain it, using silica fume will contribute incrementally to reducing CO_2 emissions but the production process is very energy intensive which attributes zero CO_2 to the fume as it is a by-product of another manufacturing process (Imbabi, Carrigan, & Mckenna, 2013). In order to develop the control mix for this study, MasterRoc MS 610 type densified Silica fume was used from BASF East Africa LTD in Nairobi.

3.1.3. Fine sand
Locally available natural sand as fine aggregate from Meru, Kenya were used in the preparation of all test specimens. Fine aggregates were sieved using 600um standard sieve size and were used in dry condition. Moreover, particle size distribution of fine sand was determined based on British Standard (BS812-103.1, 1995). The grading of fine sand used for the entire mixtures is shown in Table 7. The physical properties of fine sand in this study were also shown in Table 8.

3.1.4. Steel fibres
For this study, locally available waved wire steel fibres of 50 mm length with 0.22 mm thickness from Steel Wall Africa Nairobi branch were used for development of RRPC. By using steel fibers in concrete, greater flexural strength was observed instead of direct tension and compression (ACI Committee 544, 1988). According to Chan and Chu (2004), the reinforcing effect of steel fibers is especially critical to the mechanical properties of RPC under tension.

3.1.5. Admixtures
Commercially available superplasticiser supplied by SIKA® Company Kenya Limited in Nairobi under the commercial name Sika Viscocrete-10 were used in this study to attain workability.

3.1.6. Water
The ordinary drinking water was also used for preparation of the desired concrete mix following British Standard (BS EN 1008, 2002).

Table 8. Physical properties of Fine Sand in this study

Parameters	Result
Specific gravity	2.42
Loose density (kg/m^3)	1,438.25
Bulk density (kg/m^3)	1,612.75
Fineness modulus	3.0

Table 9. Mix design for 1 m^3 RRPC under this study

Mix No.	Content (kg/m^3)								
	Cement	Waste ceramic powder	Fine sand	Super plasticizer	Water	Steel fiber	Silica fume (SF)	Waste glass powder (GP)	Fly ash (FA)
Reference	842.00	168.00	926.00	56.00	306.00	116.00	210.00		
M1	842.00	168.00	926.00	56.00	306.00	116.00		168.00	42.00
M2	842.00	168.00	926.00	56.00	306.00	116.00		105.00	105.00
M3	842.00	168.00	926.00	56.00	306.00	116.00		52.50	157.50

3.1.7. Finely dispersed local waste powders

Waste ceramic and waste glass were collected from construction sites and crushed both through man power and crushing machine in Jomo Kenyatta University Engineering Workshops. Initially, the collected wastes were crushed with a sludge hammer using manpower. Then, the crushed products were taken to the crushing machine to make them very fine and to produce pozzolanic powders. After getting finely grained powder products, the products were sieved through man powder using 150 μm standard sieve to get finely dispersed glass powder and 300 μm standard sieve to get finely dispersed ceramic powder. Figure 1 shows the preparation of finely dispersed local waste powders for this study. Moreover, for this study, waste fly ash was collected from Bamburi Cement Limited in Kenya.

3.2. Experimental

3.2.1. Proposed mix design for recycled reactive powder concrete

For this study, RRPC was developed based on the existing mix proportions of RPC (Ahmad et al., 2015; Aïtcin et al., 1998; Kushartomo et al., 2015; Richard & Cheyrezy, 1995; So et al., 2015) through preliminary tests by replacing silica fume and quartz powder in full version by local waste materials. Since the mix design was employed using this local waste materials together with other core raw materials, the name “Recycled Reactive Powder Concrete” was given for the concrete mixture.

In general, silica fume was replaced fully by combination of paired local wastes with different percentages. It was designed using fly ash vs. finely dispersed waste glass powder at 20–80%, 50–50% and 75–25% by weight. The control mix were developed from silica fume, Portland cement, finely dispersed waste ceramic powder, superplasticizer, fine sand, water and steel fiber. For all mixes, hand mixing, standard water curing and uniform water-binder ratio of 0.25 were used. As shown in Table 9, four Mixes were utilized including the control mix.

3.2.2. Raw material characterization

In this study, the physical properties of finely dispersed local wastes such as specific gravity, color and particle size distribution (for sand, silt and clay content) were investigated. Particle size distribution was done using laser diffraction (LA950) in World Agroforestry center (ICRAF) Nairobi office. Laser diffraction particle size analysis is a rapid low cost technology for measuring particle sizes using light diffraction patterns. It relies on the fact that particles passing through a laser beam will scatter light at an angle that is directly related to their size.

Moreover, X-ray fluorescence (XRF) spectrometry analysis was conducted in Kenya Ministry of Mining to characterize the chemical composition of finely dispersed local waste samples. XRF spectrometry is an elemental analysis technique based on the principle that individual atoms, when excited by an external energy source, emit X-ray photons of a characteristic energy or wavelength. By counting the number of photons of each energy emitted from a sample, the elements present may be identified and quantitated (http://archaeometry.missouri.edu/xrf_overview.html). Accordingly, mineral analysis for the proposed raw waste materials was conducted for Silica (SiO_2), Alumina (Al_2O_3), Iron Oxide (Fe_2O_3), Calcium Oxide (CaO), Magnesium Oxide (Mgo), Sodium Oxide (Na_2O), Potassium Oxide (K_2O), Titanium Dioxide (TiO_2), Manganese Oxide (MnO) and loss of ignition.

3.2.3 Mix proportion, specimen preparation and curing procedure

For this study, the mix propositions designed in Table 9 were applied. Then, RRPC specimens were prepared based on British Standard by preparing watertight and non-absorbent 100 × 100 × 100 mm^3 cube, 100 × 200 mm^3 cylinder and 150 × 150 × 550 mm^3 prism moulds (BS 5328: Part 1, 1997; BS EN 12390-1, 2000; BS EN 12390-2, 2000).

In order to prepare specimens, dry mixing of ingredients was done for 3 min. 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 min. Then, the remaining water was added and mixing was done again until

Figure 1. Preparation of finely dispersed local waste powders (waste glass, waste ceramic).

Table 10. Physical properties and chemical compositions of local waste raw materials in this study

Parameters	Finely dispersed glass powder	Fly ash	Finely dispersed ceramic powder
Silica (SiO_2)	80	52	66
Alumina (Al_2O_3)	0.7	20	16.6
Calcium oxide (CaO)	9.4	7.3	2.5
Magnesium oxide (Mgo)	0.9	0.7	0.53
Sodium oxide (Na_2O)	6	6.3	3.36
Potassium oxide (K_2O)	0.22	1.6	1
Titanium dioxide (TiO_2)	0.1	1.14	0.72
Manganese oxide (MnO)	0.01	0.04	0.01
Iron oxide (Fe_2O_3)	0.27	6.4	6.7
Loss of ignition	1.1	2	1
Specific gravity	2.61	2.84	2.3
Color	White	Grey	Reddish white

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 them. 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 ± 2°C instead of steam curing at high temperature in conventional RPC.

3.2.4 Testing program

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 (BS EN 12390-3, 2002; BS EN 12390-4, 2000; BS En 12390-5, 2000; BS EN 12390-6, 2000) in Jomo Kenyatta University Structural Engineering laboratory.

The compressive strength and the tensile splitting strength were tested by automatically controlled universal testing machine at constant rate of loading at the age of 7, 14 and 28 days of standard water curing and the average values were reported. In addition to this, the flexural strength was determined 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 arrangements 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.

Beyond the mechanical performance, microstructural studies of the developed recycled reactive powder concrete at different percentages were the other main objective of this study. For this purpose, samples were taken from each variable that was prepared by varying finely dispersed local waste quantities at different percentages by mass to replace silica fume fully including the controls and taken for mineralogical characterization/analysis after 28 days standard curing. To observe the microstructure which enables the spatial distribution of ingredients and particles, this study were uses Bruker's X ray Diffraction D2 Phaser in World Agroforestry Center (ICRAF), Nairobi for detailed analysis of minerals within the RRPC powder specimen.

Microstructure analysis by X Ray Diffraction (XRD) were employed in this study to examine the microstructural changes of various RRPC specimens made from different percentages of the test variables. The samples for XRD analysis were collected from each test variables made from different percentages, and were then processed using the following procedures.

(1) Mill: Add 9 g of ethanol to 3 g sample then mill for 12 min.
(2) Centrifuge: Transfer sample to centrifuge tube and place them on centrifuge at 4,000 rpm for 10 min for sample to settle at the bottom.
(3) Decant ethanol.
(4) Hexane addition: Add 0.5 ml of hexane to the sample and mix well using voltex mixer.
(5) Oven drying at 80°C for 1–4 h.
(6) Sieve by 250 um.
(7) Sample deposition: Put sample in sample holders till compact using a razor blade.
(8) Measurement using all-rock approach for 30 min.
(9) Quality control.
(10) Peak identification: Identify the minerals present using EVA software.
(11) Data entry.

3.2.5 Data analysis
The results of the chemical analysis for local waste materials proposed in this study were compared using graphical descriptions with the minimum requirement for a standard pozzolana quality as per ASTM C618. Moreover, the results were analyzed statically using Microsoft Excel through tables and graphs that show the most relevant properties related to the study.

Moreover, the effects of local waste raw materials were investigated experimentally by testing their mechanical and microstructural properties. Accordingly, the results of each test were recorded and analyzed graphically using Micro soft Excel as a statistical tool. Moreover, the results of XRD analysis were analyzed graphically through images obtained from the testing machine. Additionally, the mineral compositions showing the major phases were summarized in tables.

4. Results and discussion

4.1. Material characterization
In this study, specific gravity, color and particle size distribution (for sand, silt and clay content) in each waste raw material was done. Additionally, the overall chemical compositions of the wastes as a pozzolan were evaluated. Table 10 describes the physical properties and chemical compositions of local waste raw materials in this study.

The laser analysis results of local waste raw materials in this study are illustrated in Figure 2. Except the fly ash, the major composition in each local waste is sand content followed by silt and clay. Where as in fly ash, the major composition is clay followed by silt and sand.

Table 11. Minimum requirement for Pozzolanic property of waste raw materials in this study

Minerals	Finely dispersed glass powder	Fly ash	Finely dispersed ceramic powder	Fine sand	Silica fume
Silica (SiO_2)	80	52	66	67	96.176
Alumina (Al_2O_3)	0.7	20	16.6	12.6	0.106
Iron oxide (Fe_2O_3)	0.27	6.4	6.7	8.7	0.463
Total	80.97	78.4	89.3	88.3	96.8

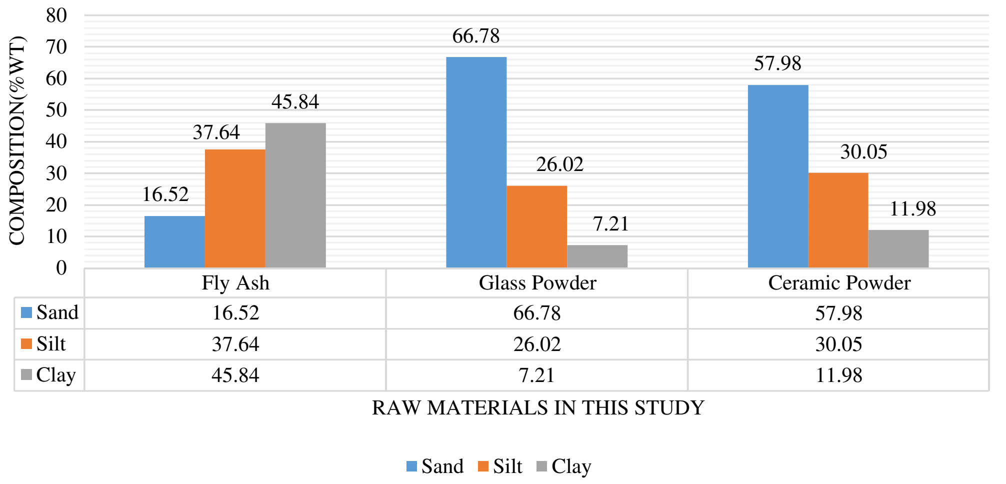


Figure 2. Particle size distribution by laser diffraction for local wastes in this study.

Moreover, 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.%.

Table 11 shows the major chemical compositions (silica, alumina and iron oxide content) of selected local wastes in this study after XRF analysis. As evaluation criteria, the sums of the three mineral components (silica, alumina and iron oxide content) in each local waste were compared with the requirement of ASTM C618 as a pozzolan.

In view of that, finely dispersed glass powder contains 80.97%; fly ash 78.4%, finely dispersed ceramic powder 89.3%, fine sand 88.3% and silica fume 96.8% by weight. The chemical compositions for the proposed raw materials were greater than 70 (by weight %). Hence, they fulfill the requirement of ASTM C618 as a pozzolan.

Setina, Gabrene, and Juhnevica (2013) had done the effect of pozzolanic additives on structure and chemical durability of concrete. It was explained that finely dispersed pozzolanic additives can act as a supplementary cementitious materials which can play a micro filler role within the concrete matrix. As a cementitious admixture and fine filler, the pozzolanic additives activate the process of mineralization.

Accordingly, as per the minimum requirement for a pozzolan, the proposed local waste raw materials will be nice pozzolanic additives which can play a micro filler role within the concrete matrix.

4.2. The effect of fly ash and waste glass powder on mechanical properties of RRPC

Concrete is one of the most common and widely used construction materials in which its properties have been well studied at macro or structural level without fully understanding the properties of the cementitious materials at the micro level. The rapid development of the characterization techniques makes it possible to characterize cementitious materials at micro/nano-scale level. The better

Table 12. Mechanical properties of RRPC containing FA and GP at different percentages

Mix designation	7 Days		14 Days		28 Days		
	Compressive strength	Split tensile strength	Compressive strength	Split tensile strength	Compressive strength	Split tensile strength	Flexural strength
Mix 1 (20%FA–80%GP)	51.60	4.753	53.13	4.759	59.41	4.771	8.428
Mix 2 (50%FA–50%GP)	51.02	4.753	59.50	4.740	62.87	4.758	8.836
Mix 3 (75%FA–25%GP)	50.80	4.645	52.54	4.735	61.47	4.773	8.249
Reference	39.60	4.55	46.73	4.68	51.83	4.76	6.134

understanding of the structure and behavior of concrete at micro/nano-scale could help to improve concrete properties and make concrete more durable (Mukhopadhyay, 2011). Characteristics like, durability, impermeability and volume stability may be important in some case of designing concrete structure but strength is the most important one since an overall picture of concrete quality is being reflected by the concrete strength (Hasan & Kabir, 2011). The fire endurance temperature of RPC is higher as compared to HPC (Liu & Huang, 2009).

For RPC, the ranges of mechanical properties are found as 130–260 MPa compressive strength; 30–60 MPa flexural tensile strength and 6–8 MPa split-tensile strength at the age of 28 days (Ahmad et al., 2015).

It is generally acknowledged that mechanical properties of concrete such as strength and stiffness are influenced directly by the physical properties of material microstructure (Pantazopoulou & Mills, 1995).

In this study, after full replacement of silica fume by fly ash and glass powder at different percentages and testing at the respected ages, its properties were identified and investigated. The mechanical performances of the recycled reactive powder concrete in this study were evaluated by compressive strength, split tensile and flexural strength. Table 12 shows the mechanical Properties of RRPC containing fly ash and waste glass powder.

The densities of the produced Recycled Reactive Powder concrete at different ages were tabulated in Table 13.

As it was observed in Table 13, the maximum densities of RRPC were observed in 50FA-50GP mix series after 28 days standard curing. Compared to the control, 0.77% greater densities were observed in 50FA-50GP mix series.

Table 13. Density of RRPC cubes containing FA and GP at testing ages

Percentage	Density (kg/m^3)		
	7 Days	14 Days	28 Days
20FA–80GP	2,310.00	2,408.00	2,305.67
50FA–50GP	2,377.67	2,413.67	2,462.67
75FA–25GP	2,310.67	2,364.33	2,362.33
Control	2,389.33	2,420.33	2,443.67

Table 14. Mineralogical composition for main mineral phases after XRD analysis of RRPC containing FA and GP

Phase	Reference	Mix 1	Mix 2	Mix 3
Albite, $NaAlSi_3O_8$	28	19.9	24.2	23.4
Calcite, $CaCO_3$	8.6	8.2	7	5.6
Microcline, $KAlSi_3O_8$	14.2	18	16.1	16.9
Portlandite, $Ca(OH)_2$	5.7	10.7	10.4	10.5
Quartz, SiO_2	26.9	25.8	26.1	24.2

In this study, compressive strength was evaluated by replacing different percentages of the proposed materials. According to the Merriam Webster dictionary, compressive strength is defined as the maximum compressive stress that under gradually applied load a given solid material will sustain without fracture.

The mean compressive strengths of three RRPC specimens produced from four categories (including control mix) containing fly ash and glass powder were presented in Figure 3.

As shown in Figure 3, the compressive strength increases with the curing age in all mix. In early age at 7 days standard curing, 51.6 MPa were observed as a maximum mean value using in mix 1 containing 20% fly ash (FA) and 80% finely dispersed glass powder (GP). However, in 14 days standard curing, 59.5 MPa maximum strength were observed in mix 2 using 50% FA-50% GP. Similarly, in 28 days standard curing, mix 2 gives a maximum mean compressive strength of 62.9 MPa.

On the other hand, the effects of fly ash and glass powder on split tensile strength of RRPC were evaluated in this study. The concrete is very weak in tension due to its brittle nature and is not expected to resist the direct tension. The concrete develops cracks when subjected to tensile forces. Thus, it is necessary to determine the tensile strength of concrete to determine the load at which the concrete members may crack.

Figure 4 shows the split tensile strength of RRPC produced in this study. As it was observed in Figure 4, the maximum split tensile strength were in Mix 3 using 75% fly ash and 25% glass powder combinations. Compared to the reference, 0.38% greater strength were achieved at 28 days standard curing.

The other mechanical strength evaluation for the developed RRPC in this study was performance evaluation by flexural strength of beams. According to dictionary of construction, flexural strength

Figure 3. Compressive strength of RRPC containing FA and GP at different percentages.

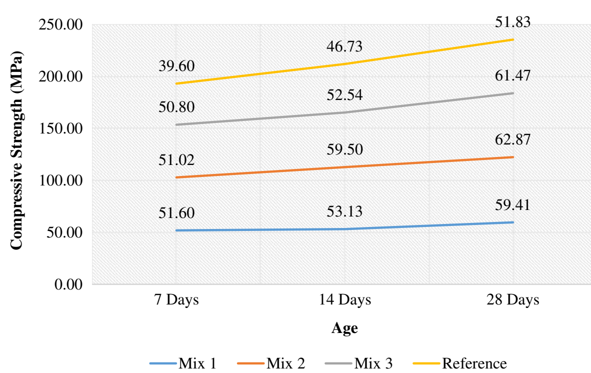


Figure 4. Split tensile strength of RRPC containing FA and GP at different percentages.

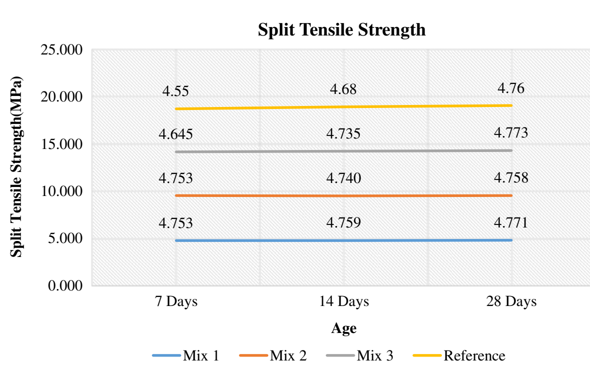
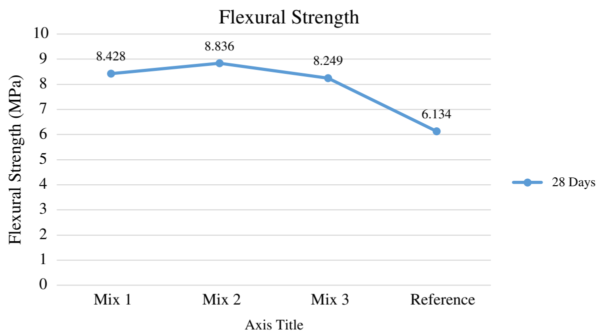


Figure 5. Flexural strength of RRPC beam containing FA and GP at different percentages.



is defined as a property of a material or structural member that indicates its ability to resist failure in bending. Figure 5 shows the flexural strength of RRPC beams with different percentages of fly ash and finely dispersed glass powder. Accordingly, a maximum flexural strength 8.8 MPa was observed using Mix 2. Compared to the reference, 30.58% was improved using the series.

As it was described in the literature part, different scholars were developed RPC at steam curing by utilization of silica fume fully in the mix design and good mechanical properties were observed.

Among those scholars, Rahman et al. (2005) developed RPC with 170–230 MPa compressive strength and 25–60 MPa flexural strength using steel fibres, highly durable and aesthetically pleasant appearance. Ahmad et al. (2015) also studied the effect of water/binder ratio (0.15, 0.175, and 0.20), cement content (1,000, 1,100, and 1,200 kg/m^3) and silica fume content (15, 20, and 25% of cement). Moreover, corresponding to an optimal dosage of 6.2% of the mass of fresh RPC, 157 kg/m3 steel fiber content were utilized in all the mixtures. From the above proposed variables, 138.9 MPa maximum compressive strength were observed at 28 days.

Additionally, So et al. (2015) manufactured modified RPC using a combination of ternary pozzolanic materials including silica fume, blast furnace slag, and fly ash. Among the modified RPC specimens, the BS10FA30 mixture (blast furnace slag 10% and fly ash 30% by weight of cement) showed excellent mechanical performance under high temperatures. The residual compressive, flexural, and splitting tensile strengths of the specimen after exposure to 1,000°C were 68, 8, and 5 MPa, respectively.

Kushartomo et al. (2015) also developed RPC by varying glass powder content at 10, 20 and 30% of cement to substitute quartz powder using steam curing at 95°C. Accordingly, 136 MPa compressive strength, 17.8 MPa split tensile strength and 23.2 MPa flexural strength maximum average values were observed using 20% glass powder substitute after 14 days. Aïtcin et al. (1998) also developed RPC for a compressive strength of 180 MPa, direct tensile strength of 7 MPa and flexural strength of 40 MPa.

From the above scholars work for conventional RPC, it can be noticed that most of the developed mixes have good mechanical strength. However, the modified RPC by So et al. using a combination of ternary pozzolanic materials including silica fume, blast furnace slag, and fly ash gave nearly the same mechanical strength with the recycled RRPC in this study.

Accordingly, 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 as well as 4.8 MPa split tensile strength using 75%GP-25%FA at 28 days standard curing.

4.3. The effect of fly ash and waste glass powder on microstructural properties of RRPC

The structural characteristic of concrete products is directly determining the final mechanical and durability properties. Many researchers have investigated its microstructure using different advanced techniques. In this study, XRD analyses were used as a microstructure technique to investigate the structural characterization so that one can determine the distinct mineralogical composition within the proposed mix.

Reactive powder concretes have been elaborated by the improvement of several parameters such as particle-size homogeneity, porosity and microstructure (Morin, Cohen-Tenoudji, Feylessoufi, & Richard, 2002). In order to improve basic characteristics of the materials such as strength and resistance, macro-level combinations are carried out to gather superior properties of two or more materials in one material (Saribiyik, Piskin, & Saribiyik, 2013). They are characterized by ultra-high mechanical performances and very low porosity (Mounanga et al., 2012).

It also described that RPC microstructure depends on heat treatment conditions and pressure applied before and during setting. XRD studies made it possible to gain better understanding of the microstructural changes induced by these procedures (Cheyrezy et al., 1995).

In the present XRD investigation, XRD analysis was carried out for RRPC containing FA and GP mixes with different percentages including their controls. Table 14 describes the mineralogical composition (mass %) of RRPC containing FA and GP in each mix series. Additionally, the X-ray diffraction pattern and analysis of RRPC mixes containing fly ash (FA) and glass powder (GP) obtained at the age of 28 days are shown in Figures 6–9.

Table 15. Mineralogical composition of RRPC containing FA and GP (mass %)

Mineral	Reference	Mix 1	Mix 2	Mix 3
Albite, $NaAlSi_3O_8$	28	19.9	24.2	23.4
Calcite, $CaCO_3$	8.6	8.2	7	5.6
Diopside, $CaMgSi_2O_6$	4.1	4.5	4.9	6.3
Halloysite, $Al_2Si_2O_5(OH)_4$	0	1.2	1.2	1
Hatrurite, Ca_3SiO_5	3.4	3.1	3	3.6
Microcline, $KAlSi_3O_8$	14.2	18	16.1	16.9
Nacrite, $Al_2Si_2O_5(OH)_4$	1.2	1.3	0	1.4
Portlandite, $Ca(OH)_2$	5.7	10.7	10.4	10.5
Quartz, SiO_2	26.9	25.8	26.1	24.2

Figure 6. XRD pattern of RRPC mix containing 20FA–80GP.

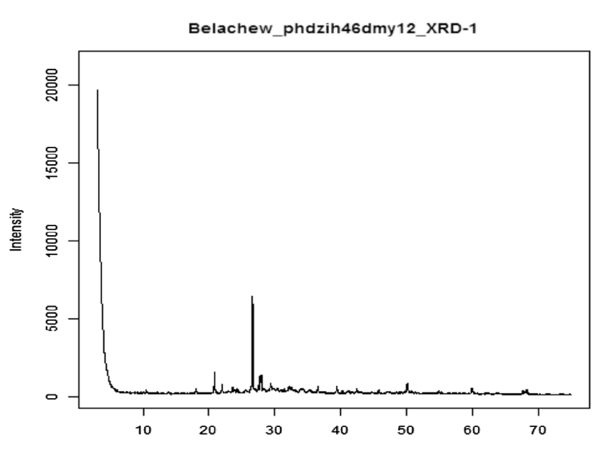


Figure 7. XRD pattern of RRPC mix containing 50FA–50GP.

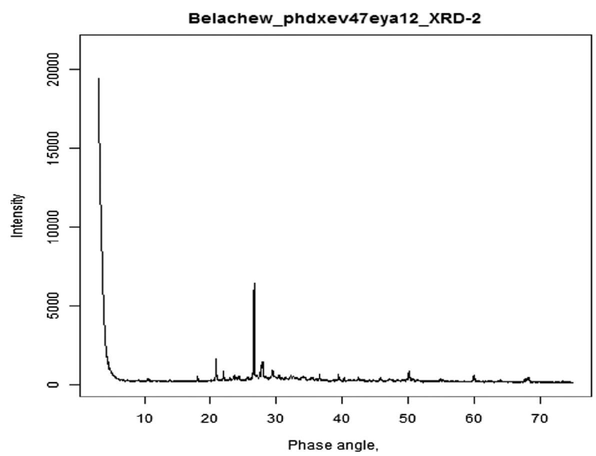


Figure 8. XRD pattern of RRPC mix containing 75FA–25GP.

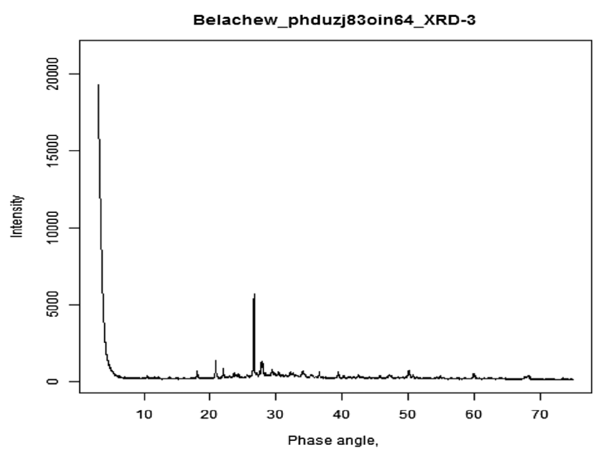
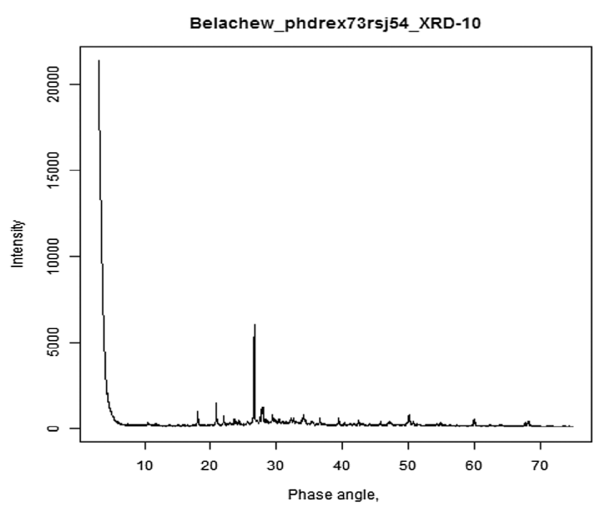


Figure 9. XRD pattern of RRPC mix containing silica fume (ref.).



From Table 15 and diagrams Figures 6–9, it can be shown that the main mineral phases of RRPC containing fly ash and glass powder are Albite ($NaAlSi_3O_8$), Calcite ($CaCO_3$), Microcline ($KAlSi_3O_8$), Portlandite ($Ca(OH)_2$) and Quartz (SiO_2). Accordingly, the mineralogical composition for main mineral phases after XRD analysis of observed values in each mix series containing FA and GP including the control were summarized in Table 14.

In summary, it is observed that all the mix series have different mineral compositions for the selected minerals. Using 50FA-50GP mix combinations in Mix 2, a maximum mineralogical composition of 26.1 for Quartz, followed by Albite with 24.2 and Microcline with 16.1 by mass (%) were observed. Using silica fume as a control, the maximum compositions are 28 for Albite, 26.9 for Quartz and 14.2 for Microcline.

5. Conclusion

For environmental and economic reasons among the few, experimental study were conducted to evaluate the mechanical and microstructural properties of RRPC containing fly ash and waste glass powder for full replacement of silica fume. Instead of steam curing at higher temperatures, standard curing was adopted for this study. Accordingly, the following conclusions can be drawn:

(1) From the material characterization result by laser analysis, sand content were the major composition in finely dispersed waste glass powder and ceramic powder. Where as in fly ash, the major composition is clay.

(2) From the material characterization result by XRF analysis, finely dispersed glass powder contains 80.97%; fly ash 78.4%, finely dispersed ceramic powder 89.3%, fine sand 88.3% and silica fume 96.8% by weight as per the requirement of ASTM C618 as a pozzolan. Accordingly, as per the minimum requirement for a pozzolan, the proposed local waste raw materials will be nice pozzolanic additives which can play a micro filler role within the concrete matrix.

(3) In all RRPC mix designs, good pozzolanic effect and good density were observed.

(4) The mechanical strengths of RRPC were increases with the curing age. Accordingly, for full replacements of silica fume by fly ash and waste glass powder, 62.9 MPa compressive strength, 4.8 MPa tensile splitting strength and 8.8 MPa flexural strength were observed after 28 days standard curing.

(5) Good mineralogical compositions were observed from the microstructural analysis. Hence, for full replacements of silica fume by fly ash and waste glass powder, 26.1% Quartz, 24.2% Albite and 16.1% Microcline by mass were observed as maximum mineralogical compositions from XRD analysis.

Thus, production of RRPC from finely dispersed local waste materials will solve raw material shortage for structural concrete and related environmental issues in Africa.

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