A Review on the Influence of Reactive Powder Concrete Ingredients on the Mechanical Properties

Ola A. Mayhoub[1,2*], El-Sayed A.R. Nasr[1], Yehia Ali[1], Mohamed Kohail[1]
[1]*Structural Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt*
[2]*El-Gazeera High Institute for Engineering and Technology, Civil Department, Cairo, Egypt*

* Corresponding author (*G15021514@eng.asu.edu.eg*)

Abstract -- Reactive Powder Concrete is a type of ultra-high-performance concrete. Improvement of microstructure, elimination of coarse aggregate, particle packing, and toughness enhancement are the main principles of RPC development. To achieve these principles, RPC is characterized by the inclusion of high cement content and pozzolanic materials that make in the other hand its production highly cost and non-environmentally friendly. In this study, the impact of using different percentages of the constituent materials of RPC and their available alternatives on compressive strength under different curing regimes are presented. Verifications are required to clarify mixing different quartz powder to quartz sand and its impact on RPC compressive strength by studying its microstructure. It was showed that curing of RPC considered to be very important aspect in its development as it significantly affects the reactivity of its constituent. Volumetric changes are considered the main problematic properties that prevent the wide use of RPC.

Index Terms: Ultrahigh-performance concrete; Reactive powder concrete; Quartz powder; Quartz sand

1.Introduction

Reactive powder concrete (RPC) belongs to the family of ultra-highperformanceConcrete. The term 'reactive powder' reflects the meaning that all the powder components in RPC are chemically reactive. Some researchers have confirmed that UHPC is not a concrete, due to the absence of coarse aggregate [1]. However, the term 'concrete' is selected rather than 'mortar' to describe UHPC due to the inclusion of fine steel fibers to enhance the ductility[2]. Microstructural improvement methods have been used to develop RPC by modifying its characteristics such as high durability, high compressive strength and superb toughness. Such criteria has been achieved through the following principles[3]–[5]:
-Improvement of microstructure and the elimination of coarse aggregate,
- The highest particle packing,
- Enhancement of toughness.

The excellent performance of RPC is attributed to the utilization of the admixtures,
superplasticizer, very fine graded quartz sand, small-sized steel fibers and low water/binder ratio in addition to the exclusion of the coarse aggregates. So, principles to produce Reactive Powder Concrete are as follows:

1.1 Improvement of microstructure and Elimination of coarse aggregate

The mechanical and the durability properties of concrete are influenced by the bond between the aggregate and the cement matrix and hence are affected by the microstructure of the ITZat which microcracks may initiate and then propagate to the cement paste [6]–[15]. The critical role of ITZ is clear when comparing stress-strain curves graphically for cement paste, aggregate and concrete under compression loading as shown in figure 1[11].

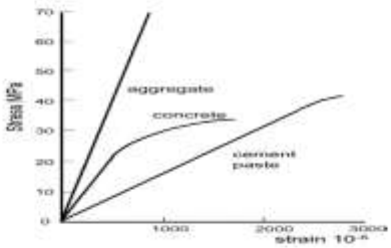

Fig.1. Comparative stress-strain curves for aggregate, paste and concrete, [11].

The cement paste and the aggregate show an obvious elastic and brittle behavior. On contrary, the concrete have a ductile behavior. This may be due to the development of multiple tiny cracks predominantly in the interfacial zone. RPC is designed by the microstructural improvement techniques, which can be carried out by close packing density through using of pozzolanic mineral admixtures that contribute also in increasing its homogeneity[16]. The addition of more fine particles as quartz powder can pack near to the aggregate surface and help in giving a very compact ITZ without obvious pores as shown in figure 2 [11], [17]. The low water /cement ratio in RPC participates greatly in decreasing its porosity[16].

Ettringiteis formed between the incompletely hydrated materials and C-S-H gel[5].The main hydration products(C-S-H gel) were homogenous, Ca(OH)2crystals are not found and ettringite is formed[17].

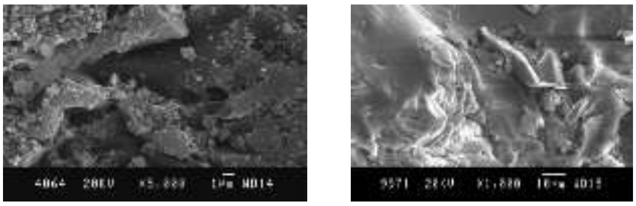

Fig.2. Microstructure of RPC showing compact ofITZ

RPC microstructure greatly depends on the condition of curing as the heat treatment and the applied pressure before and during setting. This is because the increase in the temperature leads to changes in the microstructure of ITZ and the pozzolanic activity[8]. This can be clear in the formation of crystal hydrates and xonotlite at a temperature (200-250oC)[8].

Increasingly, one of the most significant feature that enhances the microstructure of RPC and distinguishes RPC from any other classic high performance concrete HPC is the elimination of coarse aggregate and replacing it by quartz sand so as to increase the strength bond inside the matrix, to enhance homogeneity[3], [18], increase packing efficiency of particles and to decrease the mechanical effects of microstructure heterogeneity which minimize the material's internal defect like pore space and microcracks[8], [19]–[22]. Also, the elimination of coarse aggregate in RPC results in variation in some properties like the autogenous shrinkage, in which the shrinkage value of UHPC containing coarse aggregates is about 60% of RPC experimented[23].

1.2 Particle Packing

The main aim of applying particle packing models are obtaining both high mechanical strength and superior durability, in which this can be achieved by incorporating both the suitable sizes and proportions of small particles to pack the larger voids. Hence, the performance of RPC is obviously influenced by the size and the percentages of the pores which in turn affect both the type and degree of packing of its constituents[24].The small voids found in between cement and aggregate particles are filled by the more powdered particles.This in turn causes an efficient packing to the voids between cement grains so that the overall performance of the concrete mix is enhanced to a great extent[24], [25]. These can be defined through the two major analysis for particles behavior named "loosening effect" and "wall effect".

The optimum grain size distribution curve can satisfy the following curve in order to obtain the most favorable packing as shown in figure 3:

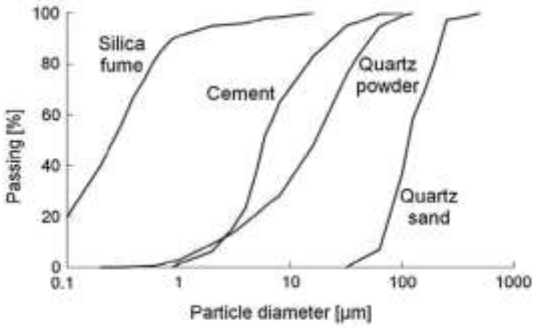

Fig.3. Grain-size distribution for RPC components[26]

So, RPC performance is enhanced by the inclusion of fine powders to the mix which is a reversal to the ordinary concrete that may be badly affected by these fine materials. These fine materials create a free large surface area that needs a high amount of C-S-H gel. The high cement dosage in RPC anticipates in forming a lot of C-S-H gel between the increased powders surface area and hence increase the packing of its particles.

Ideal gradation curve and filling properties of powdered constituents (such as cement, fly ash, silica fume, and both quartz sand and powder)are the main concepts of particle packing approach[27].

Some cement grains remain un-hydrated in RPC mix due to the low water content. These cement grains participate greatly in the granular packing of RPC's particles as their size lay between the size of the silica fume and the quartz powder, so they help in filling the gap between the other particles to be well packed as shown in figure 3. By applying the granular packing of cementitious materials in preparing RPC at W/C of about 0.20, the discontinuous capillary porosity can be achieved when only 26% of cement has been hydrated, instead of 54% for high performance concrete (W/C=0.33)[25]. The nature of the particle packing can be considered by using the following three methods: [28]–[30]: (a) Optimization particle packing curves[31]–[34],(b) Particle packing analytical models[27], [34]–[38], (c) Numerical simulations[39].

1.3 Enhancement of toughness

The absence of coarse aggregates would significantly increase drying shrinkage in RPC that may be redeemed by the addition of steel fibers [40].The inclusion of steel fibers to RPC would also enhance the cracking resistance greatly[41]. This is due to the role of fibers that control the different cracks widths by blocking the continuous developing in the diagonal cracks .

Fracture toughness properties of concrete considered to be the most important factors for the safety and durability of concrete constructions. As concrete homogeneously increases an effective fracture toughness is obtained. The fracture energy of RPC incorporating steel fiber reaches four times higher than that of non-fibrous concrete. The modified toughness index (MTI) is known as the ratio of the area of stress-strain curve to the pre-peak area of the curve and in RPC, it ranges from 2.64 to 4.65[42]. While the toughness index ranging from 0.48 for plain concrete to 0.76 for fiber concrete due to crack bridging action. The main drawback of high strength concrete is that toughness records low values and hence the inclusion of steel fibers will enhance toughness [43], [44].

To decrease the crack width and prevent its propagation, steel fibers by around 3% can be successfully used and hence significantly improve the toughness of RPC by more than 80%[42], [45], [46].

Curing of RPC has a great impact on value of toughness. This may be due to increasing the curing temperature decrease the pores ratio and hence enhance the granular packing of the concrete[47]. Also pozzolanic materials increase the concrete toughness in spite of the curing conditiondue to the increase in bond strength between cement matrix and steel fibers[48].In addition to the Nano particles that will also improve fracture toughness[49].

2. Materials of RPC

RPC contains cement, pozzolanic materials, quartz sand, quartz powder, steel fibers, water, and superplasticizers.

2.1 Cementitious Constituents

Cementitious constituents in RPC are divided into cement and pozzolanic materials. The pozzolanic materials used can be silica fume, fly ash, metakaolin, or ground granulated blast furnace slag.

RPC can be prepared by any type of cement as it is observed that there is no special requirement for the cement type (CEM I, CEM II, sulfate resistance cement, etc.).However, the most preferable cement is the high silica cement which can takes part in enhancing the mechanical properties of the concrete[3]. As for the particle size, cement fineness only may affect the choice of cement in RPC. Using higher fineness cement leads the mix to consume large amount of water[50]. The low water to cement ratio in RPC makes it necessary not to use very fine cement because it may increase the water demand to a great extent, and it could be a critical factor in RPC performance. Cement dosage in RPC ranges about 700–1000 kg/m3 to achieve ultra-high strength under very low water content. This high dosage is important to increase the hydration process forming a lot of C-S-H gel between the increased powders surface area causing the packing of its particles. However, cement hydration is incomplete in RPC, causing a lot of free cement grains. These grains play a vital role in granular packing in RPC.

Adding cement to concrete mix by large percentages has many drawbacks on both the environment and the behavior of the hardened concrete due to the high cost and increased heat of hydration that causes shrinkage problems and lower dimensional stability in long term ages. Mineral admixtures such as fly ash, blast furnace slag, and silica fume can be a feasible alternative to replace cement in RPC to overcome these problems in RPC[48], [51]–[53].

They improve the performance of concrete through the packing filling effect, activating pozzolanic reactions and accelerating the process of cement hydration which in turn allow the formation of calcium silicate hydrate (C-S-H)[20], [52], [54]–[60]. For mechanical and durability aspects, the benefits gained from incorporating pozzolanic materials in RPC are high tensile strength, high flexural strength, early compressive strength, low permeability, high resistance to chemical attack against (acids, nitrates, chlorides and sulphates), high abrasion resistance, toughness, excellent durability, high modulus of elasticity, high bond strength, enhanced pore structure and improved steel fiber bonding characteristics[20], [52], [54]–[61]. For particle packing aspects, the size of cement grains lay between both pozzolanic material particles and quartz sand particles which result in good particle filling effect and significantly minimize voids ratio.

One of the most powerful pozzolanic materials that are used in RPC is silica fume because it's a based silica material[20], [52], [55]–[61]. Increasing SF beyond 25%does not significantly changes the compressive strength of RPC[20], [45], [57].

The utilization of Blast furnace slag (GGBFS) in RPC production is very effective where GGBFS can be used in RPC as an alternative silica source[52], [62]–[78].Adding 20%fly ash as partial replacement of cement to concrete modifies the microstructure of the ITZ and improves mechanical properties to a certain extent[52], [79]–[84] specially after exposure to elevated temperatures and autoclave pressure[83], [84].

Fly ash needs less water for reaction when comparing with silica fume[48], [52], [85], [86].

High reactive MK also shows high pozzolanic reactivity and reduction in Ca(OH)2. Addition of MK to concrete reduces the porosity, increase the hydration process, enhance the resistance to chemical attack and improves durability and the pore structure [87]–[100]. MK is found to reduce both autogenous and drying shrinkage and expansion volume under steam curing due to the inclusion of large amounts of reactive AL2O3 in its constituents[88], [101]–[103].

In the recent years, in RPC a variety of nanoparticles NPs as (SiO_2, Al_2O_3, Fe_2O_3, Boron nitride)[104]–[106], Zr[107], TiO_2[108]–[112] and Nano-clay[113] have been used as additives to concrete for modifying the cement hydration, the durability and the mechanical properties of fresh and hardened concrete[107], [113]–[116], high wear resistance and excellent chloride penetration resistance[107], [108], [115], [117]–[121].

However, NP have negative effect on concrete workability as the NP adsorbs the large quantity of water due their high surface area [111], [119], [122], [123] and more cohesive [119], [124]and shows a reduction in the setting time[117]–[121].

Another drawback for NP is that it affects the concrete matrix by limiting its strength improvement as a result of particles agglomeration[108], [125]–[129]. However, sonication of powder along after mixing will show an improvement in compressive strength and other mechanical properties[123], [130].An optimal dosage of NPs must be determined which ranges between 0% to 3%[107]. The enhancement of concrete properties will be limited as the percentage of NPs increase due to the increasing trend of CH crystals orientation[107], [108], [131]. NPs exhibit the achieved properties through 3 mechanisms[107], [108], [113]–[115], [119], [132]–[148]:

-NPs have a seeding surface for the hydrate's deposition, which accelerates the hydration process.

-NPs significantly fill the gaps among large particles between the cement particles, quartz powder, quartz sand and the pozzolanic particles resulting a highly packed matrix.

-Many NPs like (Nano SiO_2[142], [149]–[155] and Nano clays[125], [147]) have strong pozzolanic reactivity, so they allow the formation of extra C-S-H gel.

2.2 Quartz Sand and Quartz Powder

To achieve perfect compactness and homogeneous matrix in addition to attain least pores, RPC must incorporate graded aggregate size between 150μm and 600μm[3], [4], [156]. It is not preferable to integrate sand particles below 150μm to prevent the interference with the largest cement particles (80–100μm) and to achieve an optimum granular packing as shown in figure 4.

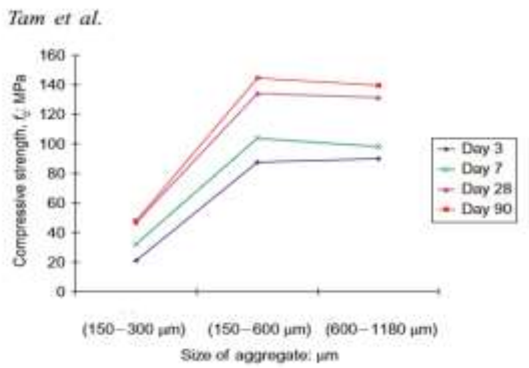

Fig.4. Effect of aggregate size on the compressive strength[22]

So the function of quartz powder in RPC is an excellent paste-aggregate interface filler that reduces the initial porosity of the mixture causing disconnected pores and resulting in very low permeability, no obvious crack existing and thereby increasing the final strength[3], [157]. Improving the microstructure of RPC can be carried out by increasing curing temperature that leads to longer C-S-H chains due to the high cement hydration. Also the high curing temperature cause an increase in the pozzolanic activity of crushed quartz and converting quartz powder into reactive silica so prompting the pozzolanic reaction and producing more CSH gel[3], [59], [158]–[160].

The addition of quartz powder resulted in an increase in compressive strength of up to 20%[161]. In RPC the quartz sand is considered to be the highest percentage ingredient with about 41% by weight of RPC and the reasonable amount of quartz powder used is RPC production reaches 20% and 35% by weight of cement[161], [162].

2.3 Water/Cement Ratio

The required quality of RPC can be achieved by allowing the water to cementitious materials ratio from (0.18 to 0.30) [163].Lower W/C ratio reduces voids between particles and thus packing density can be increased[164]. The increased packing density has a positive effect on reduced porosity in the cement matrix[164], [165].

2.4 Superplasticizers

RPC will be in more demand for water otherwise a reduction in workability will be attained[166]. Thus, a superplasticizers admixture is introduced to enhance the workability of RPC in spite of low water content [163], [166].

An appropriate dosage must be specified otherwise a chemical conflict and late setting is observed. High performance superplasticizers contain either polycarboxylate, and Naphthalene Sulfonate or Melamine Sulfonate (MS) are suitable to develop uniform RPC matrix[166]. The optimum superplasticizer dosages were as 1–3.6%, by the weight of binder at depending on W/B ratios [163].

2.5 Fibers

The addition of steel fibers enhances flexural strength, toughness, ductility and the tensile strength, and so these may resist the internal vapor pressure at a high temperature which secures RPC from spalling[167]. Both high strain and high stress is achieved by raising steel fiber content at the identical strain rates, leading to an obvious enhancement in the stiffness[168], [169].

Fibers act as crack arrester; they control the development of crack and blocking the crack growth in the concrete matrix and hence it prevents any crack from propagation[170], [171], so converts the brittle mixture into a ductile one with better crack resistance where ductility is increased by around 160% for beams with a fiber content of 2.0%[45].Small fiber content cause vertical cracks, while and diagonal cracks for higher content of steel fiber[45].

Several factors that mainly may affect their impact on concrete performance such as aspect ratio, fiber distribution, and steel fibers fraction volume, this may be as follows:

(a)Fiber Distribution

The mechanical performance of concrete depends to a high extent on the distribution of fibers in a cementitious matrix[172]. It is recommended to hold the bundled fibers, that are immersed together with a water-soluble gum[173].

(b)Aspect Ratio of Fiber (L/d)

Aspect ratio is defined as the proportion of the fiber length toits diameter. High aspect ratio gives better performance than the small one. [174].

(c)The volume fraction of steel fibers:

As the volume fraction of fibers increases, the growth of micro-cracks was restricted, in which an increase in both the fracture toughness and the indirect tensile strength (splitting strength) [45], [174], [175].

An obvious fiber interlocking and loss of workability accompanied by the inclusion of high volumes of steel fibers in concrete[44], [174], [176]. Consequently, there is an optimum fiber content for any given RPC matrix.

There are small differences between the three kinds of steel fibers (smooth, hooked and twisted).Smooth fibers is characterized by the high bond strength among RPC matrix, while hooked and twisted fibers attain additional mechanical bond [176].

3. Curing regime

The major principle of RPC production is the improvement of microstructure to be more dense by applying pressure with different heat treatment during concrete curing[3], [4], [26], [177], [178].

So the benefits from the incorporation of silica fume to RPC will be achieved only after applying curing regimes to RPC mixture [59].So, curing has an essential effect on strength development on RPC. Moreover, it was observed that standard curing is not sufficient for RPC as the rate of strength gain and hardening process will be very slowly[177]. RPC must be cured by (i)steam or hot curing or (ii)autoclave curing. The most convenient temperature for RPC curing by hot dry air may reach up to 250oC, while exposure to temperature more than 250oC may prompt a decrease in the compressive strength. This may also cause a serious microstructure deterioration due to the existence of both large numbers of pores and cracks in the surface of the specimen[47], [59], [111], [178]–[183].

To determine the main advantages of thermal curing, it can be summarized as follows:

(1) It results in a dense microstructure and a high mechanical performance to RPC by rising the ability of fresh RPC at early ages to complete the reaction between SF and portlantide that accelerates the pozzolanic reaction and therefore a new crystallized hydrates C-S-H is formed. This will increase the micro aggregate reactivity causing an increase in the inclusion matrix adhesion[26]. The increase in temperature by 10oC raises compressive strength and flexural strength of concretes by 16 MPa and 0.7 MPa[26].

This process is very essential in RPC due to the existence of high dosage of cementitious materials which will remain un-hydrated due to the low w/c ratio and hence the pozzolanic reaction between the SF and the portlantide will also remain not completed[22], [26], [181], [183]–[185].

(2) As for QP, heat treatment helps to produce secondary hydrates by the pozzolanic reaction. So crushed QP acts as pozzolanic material only at high temperature more than 90oC[177], [186].

(3) Heat treatment modifies the chemical composition of hydrated grains in RPC. This can decrease the ratio of calcium oxide to silicon dioxide. Also, it reduces the ratio of water to calcium oxide. All these reactions lead to the formation of C-S-H family which are[177], [187]:(1)Tobermorite (2)Secondary Xonotlite (3) Xonotlite.

Past researches reached compressive strength (150MPa to 310 MPa) when applying hot air curing (90oC - 250oC)[17], [59].

Autoclave curing is carried out by applying a combination of both heat and pressure curing to RPC. Compressive and flexural strengths will show a high reading of about (20-30%) when applying autoclaving compared to standard water curing, while it will show a weak effect on fracture toughness. Autoclave curing increase density and decrease porosity which will affect the mechanical performance of RPC. However, there is exact time for both pressure and temperature, beyond these critical time a negative effect on both mechanical performance and microstructure of RPC is recorded[3], [15], [26], [188], [189].

Advantages of the autoclave can be summarized as follows:

(1) Applying pre-setting pressure for 6- 12 h will eliminate the pores resulted from autogenous shrinkage but will increase the capillary pore volume due to the movement of grains. These spaces will permit the formation of additional C-S-H in the hydration process and hence the pozzolanic reaction[190].

After that, it will cause the appearance of microcracks which in turn is improved due to the expansion of aggregates after applying pressure[26], [47], [59].

(2)The achieved strength may reaches 500MPa when pre-setting pressure has values (50-100MPa)[48], [52], [53], [182], [188], [191]. The increase in temperature by 10oC increases both compressive strength and flexural strength by 4 MPa and 0.5 MPa for autoclaving[26].

(3)Increasing the adherence between paste of RPC and fibers may be improved in autoclaving, which in turn minimize the voids in the paste and hence enhance the microstructure of RPC[3], [47], [188]. So, both silica fume and steel fibers will behave more effective under autoclaving curing[59]. It improves the cohesion bond between fillers (SF and QP) and the fine crystalline cement paste[3], [26], [59], [192], [193].

(4) Autoclave curing will increase the elastic modulus and will decrease the unit weight of RPC[188].

(5) QP will be affected by autoclaving by allowing the transformation of α-C2-S-H to tobermorite structure which is desirable material in order to achieve high mechanical development[59].

(7)The more fly ash, the higher autoclave pressure is needed in order to obtain the highest strength[182].

(8) Autoclave curing will eliminate the formation of secondary ettringite due to the existence of Al^{3+} and SO_4^- ions during hydrothermal curing[3], [8], [26], [193], [194].

The disadvantages of autoclaving may be:

(1) It limits the percentage of SF in RPC because it restricts the rapid formation of different hydrated products that cause the existence of porous and weak structure[177], [195].
(2) The higher cost of autoclave instruments and steam curing chambers.
(3) The bond strength between reinforced steel bars and concrete is lowered by 50% and brittle material is achieved[177].

4. Factors affecting the compressive strength of RPC:

The main target in the development process of RPC mix design is to achieve the highest compressive strength. There are two main essential parameters that obviously affects the values of the compressive strength in which they are: (a) the selection of the proper and exact ingredients[189]. (b) the type, duration and temperature of curing[3], [177], [188], [196].

Therefore particle packing for RPC can be achieved by customizing and adapting the grading of the whole range of solid particles, incorporating the fine aggregate and the cementitious materials[197]. Table(1) shows the mix design ranges from the previous researches.

Table 1: The ranges of different mixes.[57], [162]

Cement (kg/m^3)	Quartz powder[a] (% of sand)	Quartz sand[b] (kg/m^3)	Silica fume (% of cement)	w/c	Steel fibres (% of total weight)	Superplasticizer (% of cement)
500-1100	20%-35%	815-1100	10%-30%	0.18-0.3	2%-4%	1%-2.5%

a) 10μm-45μm, b) 150μm-600μm

Curing regimes affect to a high extent the compressive strength of RPC. Autoclave and hot steam curing considered to be very effective ways to increase the compressive strength of RPC[48], [191], [198], [199]. This can be due to the enhancement of the hydration process under these curing regimes. Compressive strength may reach over 200 MPa after steam curing and greater than250 MPa after autoclaving[48].

The following figures present the relation between the compressive strength of RPC and different cement proportions.

Generally, w/c ranges from 0.18 to 0.3 and silica fume ranges from 10% to 30% from total binder ratio. All these ranges do not cause a significant change in the value of compressive strength.

The factors affecting the compressive strength of RPC under different curing regimes are:

(1) (1)Cement content

Using different cement proportion may cause a variation in the predicted compressive strength. The effect of using different cement dosage on compressive strength under standard curing, steam curing and autoclave curing can be shown on figure (5), figure(6) and figure(7) respectively.

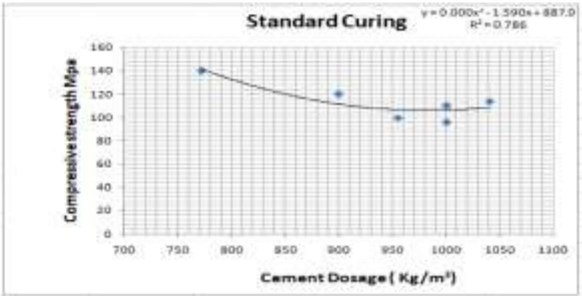

Fig.5. Effects of different cement quantities on RPC compressive strength under standard curing[59], [60], [162], [169], [182], [189]

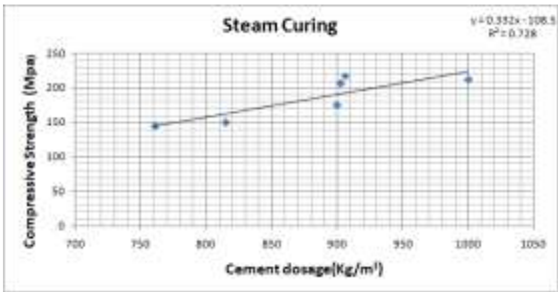

Fig.6. Effects of different cement quantities on RPC compressive strength under steam curing[22], [26], [47], [57], [188]–[190]

In RPC, steam curing considered to be very important to achieve the desired improvement in the mechanical behavior. Steam curing has a good impact on cement, pozzolanic materials and quartz powder. For cement, it enhances the hydration by increasing its rate. The increase in temperature will increase the pozzolanic reaction and causes extra C-S-H gel to be formed. Also steam curing may activate the silica found in quartz powder to carry out its reaction and hence acting as both binding and packing material.

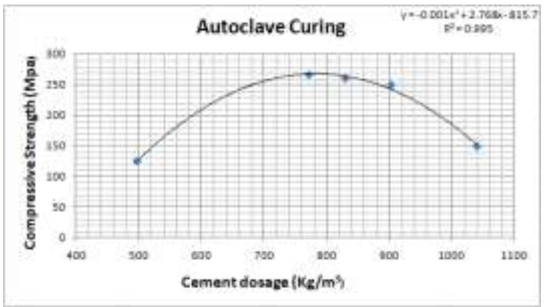

Fig.7. Effects of different cement quantities on RPC compressive strength under autoclave curing[26], [52], [59], [182], [190]

In the above figure when the cement content reaches1040 kg/m3, the compressive strength decreases due to the decrease in silica fume content used (11% from binder ratio)in this mix[182].

(2) Pozzolanic materials:

Generally, its well known that in RPC the cement dosage is obliviously high and the water/ binder ratio is very low, that surely will accelerate hydration reaction, leads to high heat of hydration and shrinkage. These drawbacks can be overcome by the partial replacement of cement with mineral admixtures.

(a)Silica fume

Replacing silica fume with cement with a certain ratio (from 15% to 25% from total binder ratio) exhibits excellent increase in RPC compressive strength. Adding more silica fume to RPC will not achieve any improvement in compressive strength.

(b)fly ash as replacement of cement

The effect of using fly ash as a replacement from cement by different percentages on the enhancement of the compressive strength under standard curing, steam curing and autoclave curing can be shown in figure(8), figure(9), and figure(10) respectively.

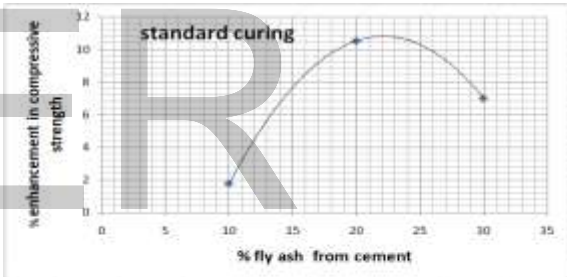

Fig.8. Effect of using different percentages of fly ash on compressive strength under standard curing[200]

The previous figure shows that there is a certain limit of fly ash content under standard curing in which the compressive strength will decrease below this limit. This may be clarified by exceeding the fly ash dosage will leave some FA particles unhydrated in the binder mix.

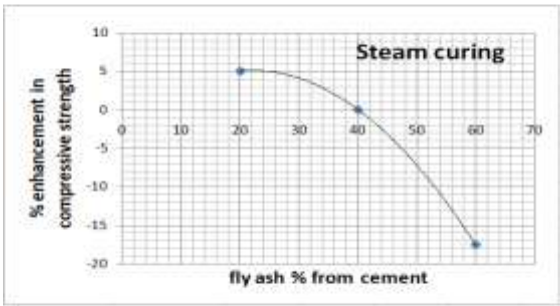

Fig.9. Effect of using different percentages of fly ash on compressive strength under steam curing[51]

From the previous figure, it is recognized that steam curing leads the mechanical strength reduction due to rapid reactions compared to the standard curing in water.

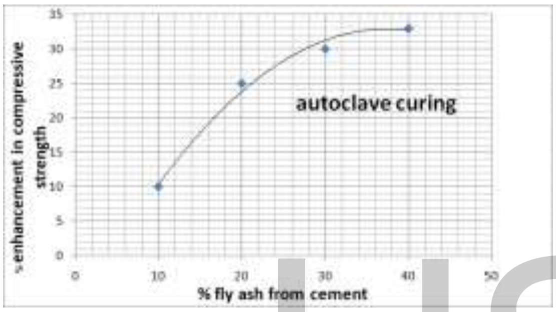

Fig.10. Effect of using different percentages of fly ash on compressive strength under autoclave curing[84]

The previous figure shows that the enhancement in the compressive strength under autoclave curing is clearly higher than that of standard curing and steam curing. This finding demonstrates that the increase in pressure during curing is appropriate for RPC mixes containing more FA. This may be due to that the pozzolanic reaction is improved and quicken by the increase in both the pressure and temperature[52], [182].The RPC mix is characterized by the increase of cement content and the decrease of water to binder ratio that leaves many cement grains unhydratedand consequently the pozzolanic reaction between the fly ash and portlandite will not be completed. So, pressure treatment accelerates the pozzolanic reaction and hence the formation of new CSH[22], [185].

(c)Ground Granulated blast furnace slag as a replacement of cement.

The inclusion of GGBFS as a replacement of cement has many advantages to both RPC and to the environment as its eco-friendly. For RPC, it was found that an improvement in the compressive strength, a reduction in both heat of hydration and shrinkage and an enhancement in microstructure of the cementitious is observed when adding 20% GGBFS replacement. This is may be due to the high ratio of capillary pores filled with C–S–H gel [53].

(d) Metakaolin as replacement of silica fume

Effect of using metakaolin as a full substitute for SF on the enhancement of the compressive strength under standard curing was observed to induce a slight reduction in compressive strength of RPC mixes by around 6% from mixes containing silica fume under standard curing [93]. RPC is expensive due to the use of large quantities of silica fume, so MK may be a better and economic alternative. It was observed that MK requires higher w/c ratio than silica fume. This, in turn, induces a slight reduction in compressive strength of RPC mixes with MK [87], [99], [201], [202].

(3) Nano Materials

Using nanomaterials by 3% replacement from cement will cause an enhancement in the compressive strength by around 12% [108].However, sonication of nanoparticles powder prior to mixing must be greatly considered to achieve strength enhancement.

(3) Quartz powder /Quartz Sand

It was observed that using different percentages of quartz powder to quartz sand will affect the values of compressive strength, this can be easily noticed in figure(11).

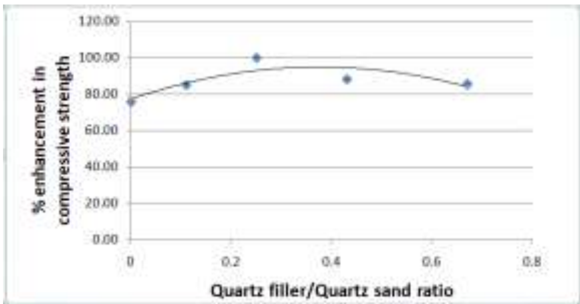

Fig.11. Effect of using different quartz filler /quartz sand ratios on compressive strength[189].

In the curve shown above in figure(11) the enhancement in compressive strength due to the inclusion of quartz powder doesn't exceed 10%. This curve needs great verifications because it shows a disagree with particle packing principles which persist to incorporate quartz powder in RPC to achieve an obvious increase in the compressive strength. So further work is needed to clarify the impact of the variance of quartz powder percentage on compressive strength by studying its microstructure.

(5) Recycled materials

(a)Rice husk ash

The effect of using rice husk ash as a partial substitute for SF by different percentages on the enhancement of the compressive strength under standard curing and steam curing can be clearly shown on figure(12) and figure (13) respectively.

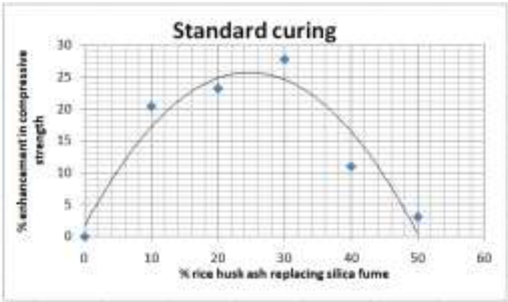

Fig.12. Effect of using rice husk ash as a partial substitute for SF by different percentages on the enhancement of the compressive strength under standard curing[159]

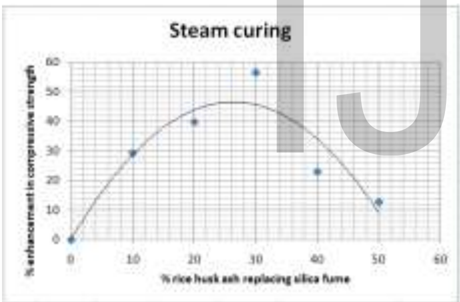

Fig.13. Effect of using rice husk ash as a partial substitute for SF by different percentages on the enhancement of the compressive strength under steam curing[159].

(b) Geopolymer

Wide use of cement in concrete production has many drawbacks to the environment as it's a high energy consumer, highly cost material, great air pollutant due to the emission of large amount of carbon dioxide gas during its production. In addition, high cement dosage may badly increase heat of hydration causing shrinkage to the concrete members. So geopolymer considered an alternative binder system which is environmentally friendly material that decreases carbon dioxide evolution. The inclusion of alkali-activated alumino-silicates has many good impacts like quick strength gain, less curing demands and good durability performance. GGGFS and SF can be used as industrial by-products in producing geopolymer RPC at ambient temperature conditions[203].

Although RPC is an ultra-high strength and high-performance concrete, it may not have a good performance in case of fire where it undergoes explosive spalling[204]–[207]. Contrarily, geopolymers are observed to possess excellent resistance to fire but achieve comparatively lower strengths.

RPGC exhibits excellent and promising results with high workability. The highest initial compressive strength reading of 76.25 MPa recorded at 24-hour testing and no explosive spalling conditions with no thermal cracking at 400oC[208]. Few studies have been done regarding the behavior of a combination of RPC and GP, while on the other hand there are a lot of studies have been conducted on both materials separately[208]. All RPGC testing is conducted at 24 hours which may be broadened to 7 or 28 days in order to fully understand the long-term changes in RPGCs with the inclusion of steel, glass or natural fibers for the enhancement of strength[208].

(c) Granite Powder

The replacement of granite powder as a full substitution of quartz powder and with a ratio of 22% of quartz sand didn't show a significant enhancement in RPC workability nor compressive strength. So RPC can be developed with the same compressive strength when replacing quartz powder with granite waste for sustainable concrete [209].

5. Conclusions

1) Improvement of microstructure, elimination of coarse aggregate, particle packing, and toughness enhancement are the main principles of RPC development.
2) RPC requires high cement content and pozzolanic materials must be used to obtain the required reactivity.
3) Curing is a vital aspect of RPC production for the enhancement of microstructure and to achieve high mechanical performance.

4) Volumetric changes are the main problematic properties that must be considered and can prevent the wide use of RPC.

6. Future Recommendation

1) RPC is not environmentally friendly. So, studies are required to replace the high cement ratio.
2) Pozzolanic materials incorporated in RPC are needed to be more economical and available.
3) Addition of nanomaterials to RPC shows good mechanical behavior, so the development of RPC containing nanomaterials must be tested using more economic and available nanomaterials. There are a lot of studies have been conducted on the impact of nanoparticles on ordinary concrete, not RPC. There is no enough knowledge about the behavior of RPC incorporating Nano clay[113].
4)There is no enough work on the behavior of RPC when replacing the quartz powder with different granite percentages.
5)Verifications and further work are needed to clarify mixing different quartz powder to quartz sand and its impact on RPC compressive strength by studying its microstructure.
(6) Few studies have been done regarding the behavior of a combination of RPC and GP, while on the other hand there are a lot of studies have been conducted on both materials separately.
(7) A gap in studying toughness has been found, where there is no standard method for measuring the toughness of UHPC and RPC.
(8) There is a shortage in data about cracking and its evaluation method for RPC.
(9) Several potential areas for future research work can be carried out on the behavior of RPC

7.References

[1] A. Sadrekarimi, “Development of a Light Weight Reactive Powder Concrete,” J. Adv. Concr. Technol., 2004.
[2] P. C. Aïtcin, “Cements of yesterday and today - concrete of tomorrow,” Cem. Concr. Res., 2000.
[3] P. Richard and M. Cheyrezy, “Composition of reactive powder concretes,” Cem. Concr. Res., vol. 25, no. 7, pp. 1501–1511, 1995.
[4] P. Richard and M. H. Cheyrezy, “Reactive powder concretes with high ductility and 200 - 800 Mpa compressive strength,” in Proceedings of V. Mohan Malhotra Symposium, 1994.
[5] D. Wang, C. Shi, Z. Wu, J. Xiao, Z. Huang, and Z. Fang, “A review on ultra high performance concrete: Part II. Hydration, microstructure and properties,” Constr. Build. Mater., vol. 96, pp. 368–377, 2015.
[6] M. Dobiszewska, A. K. Schindler, and W. Pichór, “Mechanical properties and interfacial transition zone microstructure of concrete with waste basalt powder addition,” Constr. Build. Mater., vol. 177, pp. 222–229, 2018.
[7] Y. Peng, J. Zhang, J. Liu, J. Ke, and F. Wang, “Properties and microstructure of reactive powder concrete having a high content of phosphorous slag powder and silica fume,” Constr. Build. Mater., vol. 101, pp. 482–487, 2015.
[8] M. Cheyrezy, V. Maret, and L. Frouin, “Microstructural analysis of RPC (Reactive Powder Concrete),” Cem. Concr. Res., vol. 25, no. 7, pp. 1491–1500, 1995.
[9] A. S. A. Saran, P. Magudeaswaran, and M. K. Mohammed, “Concrete Microstructure - A Review,” vol. 2, no. 12, 2016.
[10] A. Elsharief, M. D. Cohen, and J. Olek, “Influence of aggregate size, water cement ratio and age on the microstructure of the interfacial transition zone,” Cem. Concr. Res., vol. 33, no. 11, pp. 1837–1849, 2003.
[11] K. L. Scrivener, A. K. Crumbie, and P. Laugesen, “The interfacial transition zone (ITZ) between cement paste and aggregate in concrete,” Interface Sci., 2004.
[12] J. P. Ollivier, J. C. Maso, and B. Bourdette, “Interfacial transition zone in concrete,” Advanced Cement Based Materials. 1995.
[13] Xie Ping, J. J. Beaudoin, and R. Brousseau, “Effect of aggregate size on transition zone properties at the portland cement paste interface,” Cem. Concr. Res., 1991.
[14] K. Y. Liao, P. K. Chang, Y. N. Peng, and C. C. Yang, “A study on characteristics of interfacial transition zone in concrete,” Cem. Concr. Res., vol. 34, no. 6, pp. 977–989, 2004.
[15] A. M. Neville and J. J. Brooks, Properties of concrete. 2010.
[16] M. K. Maroliya, “Micro Structure Analysis of Reactive Powder Concrete,” Int. J. Eng. Res. Dev., vol. 4, no. 2, pp. 68–77, 2012.
[17] C. Wang, C. Yang, F. Liu, C. Wan, and X. Pu, “Preparation of Ultra-High Performance Concrete with common technology and materials,” Cem. Concr. Compos., 2012.
[18] C. Shi, Z. Wu, J. Xiao, D. Wang, Z. Huang, and Z. Fang, “A review on ultra high performance concrete: Part I. Raw materials and mixture design,” Constr. Build. Mater., vol. 101, pp. 741–751, 2015.
[19] A. M. T. Hassan, S. W. Jones, and G. H. Mahmud, “Experimental test methods to determine the uniaxial tensile and compressive behaviour of Ultra High Performance Fibre Reinforced Concrete(UHPFRC),” Constr. Build. Mater., 2012.
[20] Y. W. Chan and S. H. Chu, “Effect of silica fume on steel fiber bond characteristics in reactive powder concrete,” Cem. Concr. Res., vol. 34, no. 7, pp. 1167–1172, 2004.
[21] S. T. Kang, Y. Lee, Y. D. Park, and J. K. Kim, “Tensile fracture properties of an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) with steel fiber,” Compos. Struct., 2010.
[22] C. M. Tam, V. W. Y. Tam, and K. M. Ng, “Optimal conditions for producing reactive powder concrete,” Mag. Concr. Res., vol. 62, no. 10, pp. 701–716, 2010.
[23] J. Ma, M. Orgass, F. Dehn, D. Schmidt, and N. V. Tue, “Comparative Investigations on Ultra-High Performance Concrete with or without Coarse Aggregates,” Proc. Int. Symp. ultra high Perform. Concr., no. September, pp. 205–212, 2004.
[24] S. V. Kumar and M. Santhanam, “Particle packing theories and their application in concrete mixture proportioning: A review,” Indian Concr. J., 2003.

[25] O. Bonneau, C. Vernet, M. Moranville, and P. C. Aïtcin, "Characterization of the granular packing and percolation threshold of reactive powder concrete," Cem. Concr. Res., vol. 30, no. 12, pp. 1861–1867, 2000.
[26] T. Zdeb, "An analysis of the steam curing and autoclaving process parameters for reactive powder concretes," Constr. Build. Mater., vol. 131, pp. 758–766, 2017.
[27] F. de Larrard, Concrete mixture proportioning: A scientific approach. 1999.
[28] S. A. A. M. Fennis and J. C. Walraven, "Using particle packing technology for sustainable concrete mixture design," Heron, 2012.
[29] X. Chateau, "Particle packing and the rheology of concrete," in Understanding the Rheology of Concrete, 2011.
[30] N. Roussel, Understanding the Rheology of Concrete. 2011.
[31] J. A. A.H.M. Andreasen, "Ueber die Beziehungen zwischen Kornabstufungen und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten)," Kolloid-Zeitschrift 50 217–228 (in Ger., vol. Zeitschrif, pp. 217–228, 1930.
[32] D. R. D. J.E. Funk, "Predictive Process Control of Crowded Particulate Suspensions, Applied to Ceramic Manufacturing," Kluwer Acad. Press. Bost., 1994.
[33] W. J. Walker, "Persistence of granular structure during compaction processes," KONA Powder Part. J., 2003.
[34] J. Zheng, P. F. Johnson, and J. S. Reed, "Improved Equation of the Continuous Particle Size Distribution for Dense Packing," J. Am. Ceram. Soc., 1990.
[35] P. Goltermann, V. Johansen, and L. Palbøl, "Packing of aggregates: An alternative tool to determine the optimal aggregate mix," ACI Mater. J., 1997.
[36] F. de Larrard, "Ultrafine particles for the making of very high strength concretes," Cem. Concr. Res., 1989.
[37] A. K. H. Kwan, K. W. Chan, and V. Wong, "A 3-parameter particle packing model incorporating the wedging effect," Powder Technol., 2013.
[38] V. Wong and A. K. H. Kwan, "A 3-parameter model for packing density prediction of ternary mixes of spherical particles," Powder Technol., 2014.
[39] N. Roussel, M. R. Geiker, F. Dufour, L. N. Thrane, and P. Szabo, "Computational modeling of concrete flow: General overview," Cem. Concr. Res., 2007.
[40] M. A. A. Aldahdooh, N. Muhamad Bunnori, and M. A. Megat Johari, "Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method," Mater. Des., 2013.
[41] T. Ji, C. Y. Chen, and Y. Z. Zhuang, "Evaluation method for cracking resistant behavior of reactive powder concrete," Constr. Build. Mater., vol. 28, no. 1, pp. 45–49, 2012.
[42] S. Prabha, "Study on Stress-Strain Properties of Reactive Powder Concrete Under Uniaxial Compression," Int. J. Eng. Sci. Technol., vol. 2, no. 11, pp. 6408–6416, 2010.
[43] A. S. Ezeldin and P. N. Balaguru, "Normal- and High- Strength Fiber- Reinforced Concrete under Compression," J. Mater. Civ. Eng., 1992.
[44] A. Sivakumar and M. Santhanam, "Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres," Cem. Concr. Compos., 2007.
[45] M. M. S. Ridha, K. F. Sarsam, and I. A. S. Al-Shaarbaf, "Experimental Study and Shear Strength Prediction for Reactive Powder Concrete Beams," Case Stud. Constr. Mater., vol. 8, no. December 2017, pp. 434–446, 2018.
[46] L. Mao and S. J. Barnett, "Investigation of toughness of ultra high performance fibre reinforced concrete (UHPFRC) beam under impact loading," Int. J. Impact Eng., 2017.
[47] M. Ipek, K. Yilmaz, and M. Uysal, "The effect of pre-setting pressure applied flexural strength and fracture toughness of reactive powder concrete during the setting phase," Constr. Build. Mater., vol. 26, no. 1, pp. 459–465, 2012.
[48] H. Yazici, M. Y. Yardimci, S. Aydin, and A. Ş. Karabulut, "Mechanical properties of reactive powder concrete containing mineral admixtures under different curing regimes," Constr. Build. Mater., vol. 23, no. 3, pp. 1223–1231, 2009.
[49] A. Nazerigivi, H. R. Nejati, A. Ghazvinian, and A. Najigivi, "Effects of SiO2 nanoparticles dispersion on concrete fracture toughness," Constr. Build. Mater., vol. 171, pp. 672–679, 2018.
[50] P. Richard and M. Cheyrezy, "Composition of reactive powder concretes," Cem. Concr. Res., 1995.
[51] H. Yigiter, S. Aydin, H. Yazici, and M. Y. Yardimci, "Mechanical performance of low cement reactive powder concrete (LCRPC)," Compos. Part B Eng., 2012.
[52] H. Yazici, H. Yiğ iter, A. Ş. Karabulut, and B. Baradan, "Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete," Fuel, vol. 87, no. 12, pp. 2401–2407, 2008.
[53] H. Yazici, M. Y. Yardimci, H. Yiğ iter, S. Aydin, and S. Türkel, "Mechanical properties of reactive powder concrete containing high volumes of ground granulated blast furnace slag," Cem. Concr. Compos., vol. 32, no. 8, pp. 639–648, 2010.
[54] R. Siddique, "Utilization of silica fume in concrete: Review of hardened properties," Resources, Conservation and Recycling. 2011.
[55] S. Bhanja and B. Sengupta, "Influence of silica fume on the tensile strength of concrete," Cem. Concr. Res., vol. 35, no. 4, pp. 743–747, 2005.
[56] V. G. Papadakis, "Experimental investigation and theoretical modeling of silica fume activity in concrete," Cem. Concr. Res., 1999.
[57] Y. Ju, K. Tian, H. Liu, H. W. Reinhardt, and L. Wang, "Experimental investigation of the effect of silica fume on the thermal spalling of reactive powder concrete," Constr. Build. Mater., vol. 155, pp. 571–583, 2017.
[58] B. W. Langan, K. Weng, and M. A. Ward, "Effect of silica fume and fly ash on heat of hydration of Portland cement," Cem. Concr. Res., 2002.
[59] H. Yazici, E. Deniz, and B. Baradan, "The effect of autoclave pressure, temperature and duration time on mechanical properties of reactive powder concrete," Constr. Build. Mater., vol. 42, pp. 53–63, 2013.
[60] H. M. A. Hussein and R. S. Atea, "Investigation of torsional behavior and capacity of reactive powder concrete (RPC) of hollow T-beam," J. Mater. Res. Technol., no. x x, pp. 1–9, 2018.
[61] M. S. Jung, K. B. Kim, S. A. Lee, and K. Y. Ann, "Risk of chloride-induced corrosion of steel in SF concrete exposed to a chloride-bearing environment," Constr. Build. Mater., vol. 166, pp. 413–422, 2018.
[62] M. A. Megat Johari, J. J. Brooks, S. Kabir, and P. Rivard, "Influence of supplementary cementitious materials on engineering properties of high strength

concrete," Constr. Build. Mater., 2011.
[63] Y. Wang, M. An, Z. Yu, B. Han, and W. Ji, "Experimental and cellular-automata-based analysis of chloride ion diffusion in reactive powder concrete subjected to freeze–thaw cycling," Constr. Build. Mater., vol. 172, pp. 760–769, 2018.
[64] A. Bouikni, R. N. Swamy, and A. Bali, "Durability properties of concrete containing 50% and 65% slag," Constr. Build. Mater., 2009.
[65] J. Duchesne and M. A. Bérubé, "Long-term effectiveness of supplementary cementing materials against alkali-silica reaction," Cem. Concr. Res., 2001.
[66] T. H. Wee, A. K. Suryavanshi, S. F. Wong, and A. K. M. Anisur Rahman, "Sulfate resistance of concrete containing mineral admixtures," ACI Struct. J., 2000.
[67] D. D. Higgins, "Increased sulfate resistance of ggbs concrete in the presence of carbonate," Cem. Concr. Compos., 2003.
[68] K. S. Chia and M. H. Zhang, "Water permeability and chloride penetrability of high-strength lightweight aggregate concrete," Cem. Concr. Res., 2002.
[69] M. D. A. Thomas and F. A. Innis, "Effect of slag on expansion due to alkali-aggregate reaction in concrete," ACI Mater. J., 1998.
[70] B. K. Marsh, R. L. Day, and D. G. Bonner, "Pore structure characteristics affecting the permeability of cement paste containing fly ash," Cem. Concr. Res., 1985.
[71] O. Boukendakdji, E. H. Kadri, and S. Kenai, "Effects of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete," Cem. Concr. Compos., 2012.
[72] C. K. Park, M. H. Noh, and T. H. Park, "Rheological properties of cementitious materials containing mineral admixtures," Cem. Concr. Res., 2005.
[73] M. Adjoudj, K. Ezziane, E. H. Kadri, T. T. Ngo, and A. Kaci, "Evaluation of rheological parameters of mortar containing various amounts of mineral addition with polycarboxylate superplasticizer," Constr. Build. Mater., 2014.
[74] V. Sivasundaram and V. M. Malhotra, "Properties of concrete incorporating low quantity of cement and high volumes of ground granulated slag," ACI Mater. J., 1992.
[75] J. M. Khatib and J. J. Hibbert, "Selected engineering properties of concrete incorporating slag and metakaolin," Constr. Build. Mater., 2005.
[76] E. Ozbay, M. Lachemi, and U. K. Sevim, "Compressive strength, abrasion resistance and energy absorption capacity of rubberized concretes with and without slag," Mater. Struct. Constr., 2011.
[77] R. Siddique, "Utilization (recycling) of iron and steel industry by-product (GGBS) in concrete: Strength and durability properties," Journal of Material Cycles and Waste Management. 2014.
[78] P. M. Gifford and J. E. Gillott, "Alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR) in activated blast furnace slag cement (ABFSC) concrete," Cem. Concr. Res., 1996.
[79] E. G. Moffatt, M. D. A. Thomas, and A. Fahim, "Performance of high-volume fly ash concrete in marine environment," Cem. Concr. Res., 2017.
[80] G. L. Golewski, "An assessment of microcracks in the Interfacial Transition Zone of durable concrete composites with fly ash additives," Compos. Struct., vol. 200, pp. 515–520, 2018.
[81] R. Demirboğ a, "Influence of mineral admixtures on thermal conductivity and compressive strength of mortar," Energy Build., 2003.
[82] R. Siddique, "Performance characteristics of high-volume Class F fly ash concrete," Cement and Concrete Research. 2004.
[83] Y. Hefni, Y. A. El Zaher, and M. A. Wahab, "Influence of activation of fly ash on the mechanical properties of concrete," Constr. Build. Mater., vol. 172, pp. 728–734, 2018.
[84] M. A. Bahedh and M. S. Jaafar, "Ultra high-performance concrete utilizing fly ash as cement replacement under autoclaving technique," Case Stud. Constr. Mater., vol. 9, p. e00202, 2018.
[85] R. Yu, P. Spiesz, and H. J. H. Brouwers, "Development of an eco-friendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses," Cem. Concr. Compos., 2015.
[86] Ç. Yalçınkaya and H. Yazıcı, "Effects of ambient temperature and relative humidity on early-age shrinkage of UHPC with high-volume mineral admixtures," Constr. Build. Mater., 2017.
[87] M. K. Maroliya, "An Investigation on Reactive Powder Concrete containing Steel Fibers and Fly-Ash," Int. J. Emerg. Technol. Adv. Eng., vol. 2, no. 9, pp. 538–545, 2012.
[88] P. Shen, L. Lu, W. Chen, F. Wang, and S. Hu, "Efficiency of metakaolin in steam cured high strength concrete," Constr. Build. Mater., vol. 152, pp. 357–366, 2017.
[89] H. S. Kim, S. H. Lee, and H. Y. Moon, "Strength properties and durability aspects of high strength concrete using Korean metakaolin," Constr. Build. Mater., 2007.
[90] F. Cassagnabère, G. Escadeillas, and M. Mouret, "Study of the reactivity of cement/metakaolin binders at early age for specific use in steam cured precast concrete," Constr. Build. Mater., 2009.
[91] A. M. Ramezanianpour, K. Esmaeili, S. A. Ghahari, and A. A. Ramezanianpour, "Influence of initial steam curing and different types of mineral additives on mechanical and durability properties of self-compacting concrete," Constr. Build. Mater., 2014.
[92] F. Cassagnabère, M. Mouret, G. Escadeillas, P. Broilliard, and A. Bertrand, "Metakaolin, a solution for the precast industry to limit the clinker content in concrete: Mechanical aspects," Constr. Build. Mater., 2010.
[93] A. Tafraoui, G. Escadeillas, and T. Vidal, "Durability of the Ultra High Performances Concrete containing metakaolin," Constr. Build. Mater., vol. 112, pp. 980–987, 2016.
[94] R. Siddique, Waste materials and by-products in concrete. 2008.
[95] L. Courard, A. Darimont, M. Schouterden, F. Ferauche, X. Willem, and R. Degeimbre, "Durability of mortars modified with metakaolin," Cem. Concr. Res., 2003.
[96] N. J. Coleman and C. L. Page, "Aspects of the pore solution chemistry of hydrated cement pastes containing metakaolin," Cem. Concr. Res., 1997.
[97] M. F. Rojas and J. Cabrera, "The effect of temperature on the hydration rate and stability of the hydration phases of metakaolin-lime-water systems," Cem. Concr. Res., 2002.
[98] R. Siddique and J. Klaus, "Influence of metakaolin on the properties of mortar and concrete: A review," Applied Clay Science. 2009.
[99] C. Poon, L. Lam, S. C. Kou, Y. Wong, and R. Wong, "1993-Molina-DevelopmentalPILTPinduction.pdf," vol. 31, pp. 1301–1306, 2001.
[100] S. Barbhuiya, P. L. Chow, and S. Memon,

"Microstructure, hydration and nanomechanical properties of concrete containing metakaolin," Constr. Build. Mater., 2015.
[101] V. H. Nguyen, N. Leklou, J. E. Aubert, and P. Mounanga, "The effect of natural pozzolan on delayed ettringite formation of the heat-cured mortars," Constr. Build. Mater., 2013.
[102] E. Güneyisi, M. Gesoğlu, and K. Mermerdaş, "Improving strength, drying shrinkage, and pore structure of concrete using metakaolin," Mater. Struct. Constr., 2008.
[103] J. J. Brooks and M. A. Megat Johari, "Effect of metakaolin on creep and shrinkage of concrete," Cem. Concr. Compos., 2001.
[104] W. Zhang, B. Han, X. Yu, Y. Ruan, and J. Ou, "Nano boron nitride modified reactive powder concrete," Constr. Build. Mater., 2018.
[105] Z. Li and S. Di, "The Microstructure and Wear Resistance of Microarc Oxidation Composite Coatings Containing Nano-Hexagonal Boron Nitride (HBN) Particles," J. Mater. Eng. Perform., 2017.
[106] T. Wang et al., "Enhanced Thermal Conductivity of Polyimide Composites with Boron Nitride Nanosheets," Sci. Rep., 2018.
[107] D. Wang, W. Zhang, Y. Ruan, X. Yu, and B. Han, "Enhancements and mechanisms of nanoparticles on wear resistance and chloride penetration resistance of reactive powder concrete," Constr. Build. Mater., vol. 189, pp. 487–497, 2018.
[108] B. B. Han et al., "Reactive powder concrete reinforced with nano SiO2-coated TiO2," Constr. Build. Mater., vol. 148, no. May, pp. 104–112, 2017.
[109] R. Zhang, X. Cheng, P. Hou, and Z. Ye, "Influences of nano-TiO 2 on the properties of cement-based materials: Hydration and drying shrinkage," Constr. Build. Mater., 2015.
[110] S. S. Lucas, V. M. Ferreira, and J. L. B. De Aguiar, "Incorporation of titanium dioxide nanoparticles in mortars - Influence of microstructure in the hardened state properties and photocatalytic activity," Cem. Concr. Res., 2013.
[111] J. Chen, S. C. Kou, and C. S. Poon, "Hydration and properties of nano-TiO 2 blended cement composites," Cem. Concr. Compos., 2012.
[112] A. Nazari, S. Riahi, S. Riahi, S. F. Shamekhi, and A. Khademno, "Improvement the mechanical properties of the cementitious composite by using TiO2 nanoparticles," J Am. Sci, 2010.
[113] M. R. Irshidat and M. H. Al-Saleh, "Thermal performance and fire resistance of nanoclay modified cementitious materials," Constr. Build. Mater., 2018.
[114] H. Lindgreen, M. Geiker, H. Krøyer, N. Springer, and J. Skibsted, "Microstructure engineering of Portland cement pastes and mortars through addition of ultrafine layer silicates," Cem. Concr. Compos., 2008.
[115] Z. Li et al., "Effect of nano-titanium dioxide on mechanical and electrical properties and microstructure of reactive powder concrete," Mater. Res. Express, 2017.
[116] H. Li, H. G. Xiao, J. Yuan, and J. Ou, "Microstructure of cement mortar with nano-particles," Compos. Part B Eng., 2004.
[117] Y. Reches, "Nanoparticles as concrete additives: Review and perspectives," Construction and Building Materials. 2018.
[118] F. Sanchez and K. Sobolev, "Nanotechnology in concrete - A review," Constr. Build. Mater., 2010.
[119] P. Aggarwal, R. P. Singh, and Y. Aggarwal, "Use of nano-silica in cement based materials—A review," Cogent Engineering. 2015.
[120] P. K. Hou, S. Kawashima, K. J. Wang, D. J. Corr, J. S. Qian, and S. P. Shah, "Effects of colloidal nanosilica on rheological and mechanical properties of fly ash-cement mortar," Cem. Concr. Compos., 2013.
[121] S. Kawashima, J. W. T. Seo, D. Corr, M. C. Hersam, and S. P. Shah, "Dispersion of CaCO3nanoparticles by sonication and surfactant treatment for application in fly ash-cement systems," Mater. Struct. Constr., 2014.
[122] H. N. Atahan and D. Dikme, "Use of mineral admixtures for enhanced resistance against sulfate attack," Constr. Build. Mater., 2011.
[123] N. M. Barkoula, C. Ioannou, D. G. Aggelis, and T. E. Matikas, "Optimization of nano-silica's addition in cement mortars and assessment of the failure process using acoustic emission monitoring," Constr. Build. Mater., 2016.
[124] L. E. Zapata, G. Portela, O. M. Suárez, and O. Carrasquillo, "Rheological performance and compressive strength of superplasticized cementitious mixtures with micro/nano-SiO2 additions," Constr. Build. Mater., 2013.
[125] Y. Reches, K. Thomson, M. Helbing, D. S. Kosson, and F. Sanchez, "Agglomeration and reactivity of nanoparticles of SiO2, TiO2, Al2O3, Fe2O3, and clays in cement pastes and effects on compressive strength at ambient and elevated temperatures," Constr. Build. Mater., 2018.
[126] A. Nazari and S. Riahi, "TiO2nanoparticles effects on physical, thermal and mechanical properties of self compacting concrete with ground granulated blast furnace slag as binder," Energy Build., 2011.
[127] T. Meng, Y. Yu, X. Qian, S. Zhan, and K. Qian, "Effect of nano-TiO 2 on the mechanical properties of cement mortar," Constr. Build. Mater., 2012.
[128] E. Ghafari, H. Costa, and E. Júlio, "Critical review on eco-efficient ultra high performance concrete enhanced with nano-materials," Constr. Build. Mater., 2015.
[129] B. Y. Lee, A. R. Jayapalan, and K. E. Kurtis, "Effects of nano-TiO 2 on properties of cement-based materials," Mag. Concr. Res., 2013.
[130] M. H. Zhang, J. Islam, and S. Peethamparan, "Use of nano-silica to increase early strength and reduce setting time of concretes with high volumes of slag," Cem. Concr. Compos., 2012.
[131] A. Nazari and S. Riahi, "Abrasion resistance of concrete containing SiO2and Al2O,3nanoparticles in different curing media," Energy Build., 2011.
[132] X. He and X. Shi, "Chloride Permeability and Microstructure of Portland Cement Mortars Incorporating Nanomaterials," Transp. Res. Rec. J. Transp. Res. Board, 2008.
[133] N. Farzadnia, A. A. Abang Ali, R. Demirboga, and M. P. Anwar, "Effect of halloysite nanoclay on mechanical properties, thermal behavior and microstructure of cement mortars," Cem. Concr. Res., 2013.
[134] A. Hakamy, F. U. A. Shaikh, and I. M. Low, "Characteristics of hemp fabric reinforced nanoclay-cement nanocomposites," Cem. Concr. Compos., 2014.
[135] M. R. Irshidat, M. H. Al-Saleh, and S. Sanad, "Effect of nanoclay on expansive potential of cement mortar due to alkali-silica reaction," ACI Mater. J., 2015.
[136] J. Björnström, A. Martinelli, A. Matic, L. Börjesson, and I. Panas, "Accelerating effects of colloidal nano-silica for beneficial calcium-silicate-hydrate formation in cement," Chem. Phys. Lett., 2004.
[137] P. Hou, S. Kawashima, D. Kong, D. J. Corr, J. Qian,

and S. P. Shah, "Modification effects of colloidal nanoSiO2 on cement hydration and its gel property," Compos. Part B Eng., 2013.
[138] J. J. Thomas, H. M. Jennings, and J. J. Chen, "Influence of nucleation seeding on the hydration mechanisms of tricalcium silicate and cement," J. Phys. Chem. C, 2009.
[139] A. R. Jayapalan, B. Y. Lee, and K. E. Kurtis, "Effect of nano-sized titanium dioxide on early age hydration of Portland cement," in Nanotechnology in Construction 3, 2009.
[140] H. Li, M. hua Zhang, and J. ping Ou, "Abrasion resistance of concrete containing nano-particles for pavement," Wear, 2006.
[141] H. Li, M. hua Zhang, and J. ping Ou, "Flexural fatigue performance of concrete containing nano-particles for pavement," Int. J. Fatigue, 2007.
[142] B. W. Jo, C. H. Kim, and J. H. Lim, "Characteristics of cement mortar with nano-SiO 2 particles," ACI Mater. J., 2007.
[143] K. Sobolev, I. Flores, R. Hermosillo, and L. M. Torres-Martínez, "Nanomaterials and Nanotechnology for High-Performance Cement Composites," in ACI Session on "Nanotechnology of Concrete: Recent Developement and Future Perspective"., 2006.
[144] W. Li, C. Long, V. W. Y. Tam, C. S. Poon, and W. Hui Duan, "Effects of nano-particles on failure process and microstructural properties of recycled aggregate concrete," Constr. Build. Mater., 2017.
[145] M. Antoni, J. Rossen, F. Martirena, and K. Scrivener, "Cement substitution by a combination of metakaolin and limestone," Cem. Concr. Res., 2012.
[146] W. Y. Kuo, J. S. Huang, and C. H. Lin, "Effects of organo-modified montmorillonite on strengths and permeability of cement mortars," Cem. Concr. Res., 2006.
[147] T. P. Chang, J. Y. Shih, K. M. Yang, and T. C. Hsiao, "Material properties of portland cement paste with nano-montmorillonite," J. Mater. Sci., 2007.
[148] M. S. Morsy, H. A. Aglan, and M. M. Abd El Razek, "Nanostructured zonolite-cementitious surface compounds for thermal insulation," Constr. Build. Mater., 2009.
[149] J. Moon, M. M. Reda Taha, K. S. Youm, and J. J. Kim, "Investigation of pozzolanic reaction in nanosilica-cement blended pastes based on solid-state kinetic models and29SI MAS NMR," Materials (Basel)., 2016.
[150] J. J. Gaitero, W. Zhu, and I. Campillo, "Multi-scale Study of Calcium Leaching in Cement Pastes with Silica Nanoparticles," Nanotechnol. Constr. 3, 2009.
[151] M. Monasterio et al., "Effect of addition of silica- and amine functionalized silica-nanoparticles on the microstructure of calcium silicate hydrate (C-S-H) gel," J. Colloid Interface Sci., 2015.
[152] P. Mondal, S. Shah, L. Marks, and J. Gaitero, "Comparative Study of the Effects of Microsilica and Nanosilica in Concrete," Transp. Res. Rec. J. Transp. Res. Board, 2010.
[153] J. J. Gaitero, Y. S. De Ibarra, E. Erkizia, and I. Campillo, "Silica nanoparticle addition to control the calcium-leaching in cement-based materials," in Physica Status Solidi (A) Applications and Materials Science, 2006.
[154] Y. Qing, Z. Zenan, K. Deyu, and C. Rongshen, "Influence of nano-SiO2addition on properties of hardened cement paste as compared with silica fume," Constr. Build. Mater., 2007.
[155] J. Y. Shih, T. P. Chang, and T. C. Hsiao, "Effect of nanosilica on characterization of Portland cement composite," Mater. Sci. Eng. A, 2006.
[156] N. M. Azmee and N. Shafiq, "Ultra-high performance concrete: From fundamental to applications," Case Stud. Constr. Mater., vol. 9, 2018.
[157] C. M. Tam, V. W. Y. Tam, and K. M. Ng, "Assessing drying shrinkage and water permeability of reactive powder concrete produced in Hong Kong," Constr. Build. Mater., vol. 26, no. 1, pp. 79–89, 2012.
[158] H. Zanni, M. Cheyrezy, V. Maret, S. Philippot, and P. Nieto, "Investigation of hydration and pozzolanic reaction in reactive powder concrete (RPC) using 29Si NMR," Cem. Concr. Res., 1996.
[159] M. Vigneshwari, K. Arunachalam, and A. Angayarkanni, "Replacement of silica fume with thermally treated rice husk ash in Reactive Powder Concrete," J. Clean. Prod., vol. 188, pp. 264–277, 2018.
[160] N. Van Tuan, G. Ye, K. Van Breugel, A. L. A. Fraaij, and D. D. Bui, "The study of using rice husk ash to produce ultra high performance concrete," Constr. Build. Mater., 2011.
[161] L. A. Qureshi, R. M. Tasaddiq, and B. Ali, "Effect of Quartz Content on Physical Parameters of Locally Developed Reactive Powder Concrete," no. January, 2018.
[162] P. N. Hiremath and S. C. Yaragal, "Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete," Constr. Build. Mater., vol. 141, no. October, pp. 271–288, 2017.
[163] S. Ahmad, A. Zubair, and M. Maslehuddin, "Effect of the key mixture parameters on shrinkage of reactive powder concrete," Sci. World J., 2014.
[164] K. Rahmani and A. Shamsai, "Effect of Water and Cement Ratio on Compressive Strength and Abrasion of Microsilica Concrete," Middle-East J. …, 2012.
[165] G. Long, X. Wang, and Y. Xie, "Very-high-performance concrete with ultrafine powders," Cem. Concr. Res., 2002.
[166] S. Ahmad, A. Zubair, and M. Maslehuddin, "Effect of key mixture parameters on flow and mechanical properties of reactive powder concrete," Constr. Build. Mater., vol. 99, pp. 73–81, 2015.
[167] M. Abid, X. Hou, W. Zheng, and R. R. Hussain, "High temperature and residual properties of reactive powder concrete – A review," Constr. Build. Mater., vol. 147, no. 519, pp. 339–351, 2017.
[168] X. Hou, S. Cao, Q. Rong, W. Zheng, and G. Li, "Effects of steel fiber and strain rate on the dynamic compressive stress-strain relationship in reactive powder concrete," Constr. Build. Mater., vol. 170, pp. 570–581, 2018.
[169] A. Al-Tikrite and M. N. S. Hadi, "Mechanical properties of reactive powder concrete containing industrial and waste steel fibres at different ratios under compression," Constr. Build. Mater., 2017.
[170] P. Tjiptobroto and W. Hansen, "Tensile strain hardening and multiple cracking in high-performance cement-based composites containing discontinuous fibers," ACI Mater. J., 1993.
[171] G. Melián, G. Barluenga, and F. Hernández-Olivares, "Toughness increase of self compacting concrete reinforced with polypropylene short fibers," Mater. Construcción; Vol 60, No 300, 2010.
[172] F. A. Farhat, D. Nicolaides, A. Kanellopoulos, and B. L. Karihaloo, "High performance fibre-reinforced cementitious composite (CARDIFRC) - Performance and application to retrofitting," Eng. Fract. Mech., 2007.
[173] K. Jain and B. Singh, "Deformed steel fibres as minimum shear reinforcement — An investigation," Structures, 2016.

[174] P. J. M. B. C.W. Hoy, "Interaction and packing of fibres: Effects on the mixing process," in Third International RILEM Workshop on High Performance Fiber Reinforced Cement , 1999.
[175] B. Mobasher, H. Stang, and S. P. Shah, "Microcracking in fiber reinforced concrete," Cem. Concr. Res., 1990.
[176] K. Wille, S. El-Tawil, and A. E. Naaman, "Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading," Cem. Concr. Compos., 2014.
[177] P. N. Hiremath and S. C. Yaragal, "Effect of different curing regimes and durations on early strength development of reactive powder concrete," Constr. Build. Mater., vol. 154, no. July, pp. 72–87, 2017.
[178] Y. S. Tai, H. H. Pan, and Y. N. Kung, "Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800 °c," Nucl. Eng. Des., vol. 241, no. 7, pp. 2416–2424, 2011.
[179] W. Zheng, H. Li, and Y. Wang, "Compressive behaviour of hybrid fiber-reinforced reactive powder concrete after high temperature," Mater. Des., 2012.
[180] S. Philippot, S. Masse, H. Zanni, P. Nieto, V. Maret, and M. Cheyrezy, "29Si NMR study of hydration and pozzolanic reactions in reactive powder concrete (RPC)," in Magnetic Resonance Imaging, 1996.
[181] A. Cwirzen, "The effect of the heat-treatment regime on the properties of reactive powder concrete," Adv. Cem. Res., 2007.
[182] T. Chen, X. Gao, and M. Ren, "Effects of autoclave curing and fly ash on mechanical properties of ultra-high performance concrete," Constr. Build. Mater., vol. 158, pp. 864–872, 2018.
[183] S. L. Mak and K. Torii, "Strength development of high strength concretes with and without silica fume under the influence of high hydration temperatures," Cem. Concr. Res., 1995.
[184] A. Kamen, E. Denarié, and E. Brühwiler, "Thermal effects on physico-mechanical properties of ultra-high-performance fiber-reinforced concrete," ACI Mater. J., 2007.
[185] K. M. Ng, C. M. Tam, and V. W. Y. Tam, "Studying the production process and mechanical properties of reactive powder concrete: a Hong Kong study," Mag. Concr. Res., 2010.
[186] S. Abbas, A. M. Soliman, and M. L. Nehdi, "Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fiber lengths and dosages," Constr. Build. Mater., 2015.
[187] C. Tam and V. W. Tam, "Microstructural behaviour of reactive powder concrete under different heating regimes," Mag. Concr. Res., 2012.
[188] M. Ipek, K. Yilmaz, M. Sümer, and M. Saribiyik, "Effect of pre-setting pressure applied to mechanical behaviours of reactive powder concrete during setting phase," Constr. Build. Mater., vol. 25, no. 1, pp. 61–68, 2011.
[189] D. Mostofinejad, M. R. Nikoo, and S. A. Hosseini, "Determination of optimized mix design and curing conditions of reactive powder concrete (RPC)," Constr. Build. Mater., vol. 123, pp. 754–767, 2016.
[190] M. Helmi, M. R. Hall, L. A. Stevens, and S. P. Rigby, "Effects of high-pressure/temperature curing on reactive powder concrete microstructure formation," Constr. Build. Mater., vol. 105, pp. 554–562, 2016.
[191] J. Dugat, N. Roux, and G. Bernier, "Mechanical properties of reactive powder concretes," Mater. Struct., 1996.
[192] C. Lehmann, P. Fontana, and U. Müller, "Evolution of Phases and Micro Structure in Hydrothermally Cured Ultra-High Performance Concrete (UHPC)," Nanotechnol. Constr. 3 - Proc. NICOM3 , 2009.
[193] W. Kurdowski, Cement and concrete chemistry. 2014.
[194] H. Taylor, "Cement chemistry," Acad. Press, 1990.
[195] C. M. Aldea, F. Young, K. Wang, and S. P. Shah, "Effects of curing conditions on properties of concrete using slag replacement," Cem. Concr. Res., 2000.
[196] J. P. Bhusari and K. S. Gumaste, "Characterization of Reactive Powder Concrete for its mechanical properties," Int. J. Civ. Eng. Technol., vol. 8, no. 5, 2017.
[197] S. Pradhan, S. Kumar, and S. V. Barai, "Recycled aggregate concrete: Particle Packing Method (PPM) of mix design approach," Constr. Build. Mater., vol. 152, pp. 269–284, 2017.
[198] Y. Ruan et al., "Mechanical behaviors of nano-zirconia reinforced reactive powder concrete under compression and flexure," Constr. Build. Mater., vol. 162, pp. 663–673, 2018.
[199] P. Hiremath and S. C. Yaragal, "Investigation on Mechanical Properties of Reactive Powder Concrete under Different Curing Regimes," Mater. Today Proc., vol. 4, no. 9, pp. 9758–9762, 2017.
[200] W. Wang, S. J. Chen, F. Basquiroto De Souza, B. Wu, and W. H. Duan, "Exfoliation and dispersion of boron nitride nanosheets to enhance ordinary Portland cement paste," Nanoscale, 2018.
[201] A. Tafraoui, G. Escadeillas, S. Lebaili, and T. Vidal, "Metakaolin in the formulation of UHPC," Constr. Build. Mater., 2009.
[202] M. A. Caldarone, High-Strength Concrete A practical guide. 2009.
[203] P. S. Ambily, K. Ravisankar, C. Umarani, J. K. Dattatreya, and N. R. Iyer, "Development of ultra-high-performance geopolymer concrete," Mag. Concr. Res., 2014.
[204] W. Zheng, B. Luo, and Y. Wang, "Compressive and tensile properties of reactive powder concrete with steel fibres at elevated temperatures," Constr. Build. Mater., 2013.
[205] K. P. Tian et al., "Effects of Silica Fume Addition on the Spalling Phenomena of Reactive Powder Concrete," Appl. Mech. Mater., 2012.
[206] G. F. Peng, Y. R. Kang, Y. Z. Huang, X. P. Liu, and Q. Chen, "Experimental research on fire resistance of reactive powder concrete," Adv. Mater. Sci. Eng., 2012.
[207] H. S. So, J. B. Yi, J. Khulgadai, and S. Y. So, "Properties of strength and pore structure of reactive powder concrete exposed to high temperature," ACI Mater. J., 2014.
[208] A. M. U. T. Kannangara, "The Behaviour of Reactive Powder Geopolymer Concrete at Elevated Temperature," Victoria University, 2018.
[209] S. Singh, R. Nagar, V. Agrawal, A. Rana, and A. Tiwari, "Sustainable utilization of granite cutting waste in high strength concrete," J. Clean. Prod., 2016.