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REACTIVE POWDER CONCRETE; COMPOSITION, DEVELOPMENT AND APPLICATIONS: A REVIEW

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ABSTRACT

In construction industry of today, the use of concrete types which have superior characteristics compared to normal strength concrete (NSC) has attracted significant interest worldwide. The popular general term to describe a special type of concrete with superior characteristics is high performance concrete (HPC). This paper presents a review about reactive powder concrete (RPC), which is a type of HPC that is used in certain applications and environments. The RPC mainly consists of cement, fine aggregate, silica fume, superplasticizer and water. Steel fibers are usually added for ductility purposes. The review presents the RPC in terms of mix design, compressive strength, the main components, use of fibers and durability. Then, the review reports the applications and experimental studies of the RPC in infrastructure including recent studies for the RPC as a new repairing-strengthening material. Last, the significance of the review and conclusions are highlighted.

KEYWORDS

Concrete, Reactive Powder Concrete (RPC), Fibers, Durability, Strengthening.

1. INTRODUCTION

In 1995, Richard and Cheyrezy developed an exceptional type of concrete known as Reactive Powder Concrete (RPC), which was distinguished with its excellent strength and ductility. The RPC is composed of a high proportion of finely ground cement, fine aggregates (sometimes including quartz flour), silica fume, superplasticizers, water, and steel fibers. The inclusion of steel fibers within the RPC mix design is essential for ductility requirements. Although the RPC is more expensive per unit volume compared to conventional concrete (Sanchayan and Foster, 2015), it achieves remarkable compressive strength ranging from 170 MPa to 800 MPa, as demonstrated in its initial prototype by Richard and Cheyrezy (1995). The high strength of the RPC decreases the required reinforcement and cross-sectional dimensions for the RPC structural members compared to the normal strength reinforced concrete (RC) members (Sadrekarimi, 2004). In other words, the distinctive strength of the RPC enables less material of RPC to achieve the same structural strength as traditional concrete. Today, the RPC is widely available in the commercial market in numerous countries, making it a practical and accessible choice for various construction applications (Sanchayan and Foster, 2015).

When compared to high strength concrete (HSC) with compressive strength of 80 MPa, the RPC has significantly higher characteristics in terms of compressive strength, tensile strength, flexural strength, modulus of elasticity, freeze-thaw resistance, abrasion resistance and carbonation resistance. Also, the RPC has low porosity results in superior durability and transport properties, which in turn leads to suitability for using the RPC in some special applications (Kosmatka et al., 2003).

It is clear that the RPC is an innovative category of concrete has a significant impact on construction industry. However, a comprehensive review about RPC could be limited. Therefore, this paper presents a comprehensive effectively summarized review about the RPC. The review is presented in terms of mix design, compressive strength, the main components, use of fibers, durability, recent applications in infrastructure as well as experimental studies and potential of RPC as strengthening and repairing material.

2. COMPOSITION AND MICROSTRUCTURE OF THE RPC

The RPC is more similar to mortar than to conventional concrete because it lacks coarse aggregate in its composition. A special technique was applied to prepare the RPC by Richard and Cheyrezy (1995). The technique depended mainly on the enhancement of the homogeneity, compactness and microstructure of the RPC compared to the normal strength concrete (NSC). The homogeneity was developed due to the absence of course aggregate, while the compact-ability was improved by optimizing the particle system of the RPC and applying pressure through setting time as a curing technique. The microstructure of the RPC was improved by applying the after-setting heat curing (Richard and Cheyrezy, 1995).

The mechanical and physical characteristics of the RPC were also improved by enhancing the microstructure due to the application of heat curing and the presence of an active filler such as silica fume. Consequently, the microstructure for the RPC has two distinguished characteristics namely; the dense-compacted portion of the Calcium Hydrated Silicates and the considerable adhesive strength between the Calcium Hydrated Silicates from one side and the mineral admixture, the sand and the fibers from the other side (Denisiewicz and Kuczma, 2013).

3. MIX DESIGN AND COMPRESSIVE STRENGTH OF THE RPC

Over the last three decades, many researchers prepared the RPC by using the regionally available materials with different mix proportions and curing techniques. Table 1 presents a summary for the proportions of some RPC mixes with different curing techniques and gained compressive strength. The studies showed that RPC which was cured under normal curing conditions (water tank with a temperature about 25 ^{o}C), had compressive strength varies between 84 MPa to 212 MPa (Richard and Cheyrezy, 1995; Lee and Chisholm, 2005; Menefy, 2007; Chang et al., 2009; Tam et al., 2010; Mostofinejad et al., 2016; Hiremath and Yaragal, 2017; Al-Tikrite and Hadi, 2017; Algburi et al., 2019, b).

The studies demonstrated also that achieving compressive strengths more than 212 MPa for the RPC requires the use of accelerated curing (AC) techniques. Commonly employed AC methods include hot water baths, steam chambers, pre-setting pressure applications, and autoclave techniques. (Richard and Cheyrezy, 1995; Shaheen and Shrive, 2006; Yunsheng et al., 2008; Aydin et al., 2010; Maroliya, 2012). Fig.1 compares the results of compressive strength for the Normally cured (NC) RPC and Accelerated curing (AC) RPC. The figure emphases that highest compressive strength for the NC-RPC is 212 MPa. On the other hand, AC-RPC achieved RPC up to 800 MPa. It is important to note that all mixes of NC-RPC in Fig. 1 have no fibers whereas, all mixes of AC-RPC in Fig. 1 have different proportions of steel fibers. Another important note that, Liu and Huang (2009) prepared RPC with compressive strength of only 75 MPa cured with autoclave and assumed to be highly flowable. Other study conducted by Ahmed et al. (2015) also showed that increase the flow-ability of the RPC leads to a decrease in the compressive strength of the RPC.

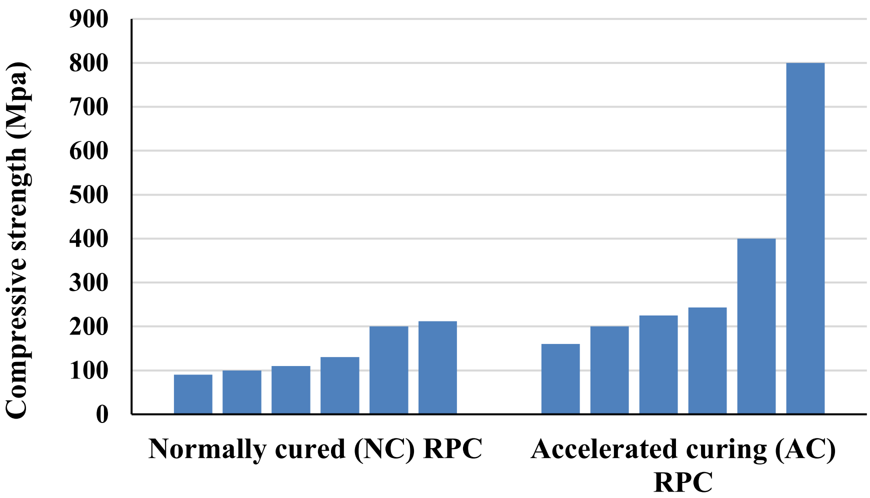

Fig. 1. Compressive strength of NC-RPC and AC-RPC

Table 1. Summary of proportions (% of cement) for some RPC mixes with different curing method and compressive strength

Author	Cement	Silica fume	Fine aggregate	Crushed quartz or Silica flour	Superplasticizer	Steel fiber	Water	AC	Compressive strength (MPa)
(Richard and Cheyrezy, 1995)	100	25	110	-	1.6	-	17	No	200
Lee and Chisholm (2005)	100	25	110	-	74*	-	26	No	99-212
Shaheen and Shrive (2006)	100	23	110	39	1.9	-	17	Yes	243
Menefy (2007)	100	30	143	30	6.4	-	22	No	109-130
Yunsheng et al. (2008)	100	25	125	-	4.25	4^	15#	Yes	225
Aydin et al. (2010)	100	30	85	21	5.21	25	13#	Yes	200-400
Tam et al. (2010)	100	32	143	29	2.5	-	23#	No	108
Maroliya (2012)	100	32	150	36	4	20	23	Yes	160-800
Mostofinejad et al. (2016)	100	25	-	100	3	-	22	No	85
Hiremath and Yaragal (2017)	100	20	-	20	1.5	-	18#	No	110
Al-Tikrite and Hadi (2017)	100	24	102	1	5.5	-	16	No	100
Hadi et al. (2018, a)	100	25	105	-	5.7	13	20	No	110
Algburi et al. (2019, a)	100	25	105	-	5.7	13	20	No	110
Algburi et al. (2019, b)	100	25	105	-	5.5	-	18	No	90

Notes:

0.74* is percentage from solid weight of cement.

0.04^ is volume fraction.

0.15#, 0.23#, 13# and 0.18# are water to binder ratios where binder = cement + silica fume.

The RPC has a dense structure. Therefore, the mixing procedure has to be considered during the production of this special category of concrete. The Mixing procedure of the RPC was presented in the experimental studies with considerable attention by the authors. The studies proposed sequent steps with approximate mixing intervals to achieve the target rheology. The main steps of mixing process can be summarized as following; mixing of dray binder materials (cement + silica fume); charge the mixer with the dray materials (cement + silica fume + sand) and mixing the dray materials for about (2-5) minutes; add half to two-thirds of the (water + superplasticizer) and mixing for about (10-20) minutes; add the remaining of the (water + superplasticizer) and mixing for about 5 minutes; add steel fibers and mixing for about 5 minutes (Al-Tikrite and Hadi, 2017; Akhnoukh and Soares, 2018; Algburi et al., 2019 (b)).

4. MAIN COMPONENTS OF THE RPC

Similar to NSC, the properties of the RPC are highly influenced by the characteristics of its constituent materials. Key factors that significantly impact RPC's performance include the cement content and composition, the water-to-binder ratio, and the reactivity of mineral admixtures (silica fume, fly ash, ground granulated blast furnace slag) and superplasticizer base material.

The production of RP involves the use of various types of Portland cement, including ordinary cement, sulfate-resistant cement, and high early-strength cement. The selection of cement type depends on specific requirements such as strength, durability, and cost considerations (Menefy, 2007). While different types of cement have been successfully used in RPC preparation, the most commonly used cement is ordinary Portland cement with an approximate composition of: C3S (60%), C2S (22%), C3A (3.8%), and C4AF (7.4%) (Cheyrezy et al., 1995).

The choice of cement type depends mainly on the category of superplasticizer used. Cement with low C3A content inclines to yield better results due to its compatibility with superplasticizers. While high fineness in cement is often desirable, it can increase water demand. Cement with a high silica modulus has been found to be the most effective choice for flowability and mechanical properties. However, high-silica-modulus cement is not applicable everywhere due to its slow setting rate. Alternatively, quick-setting, high-performance cement can provide similar mechanical properties to high-silica-modulus cement, despite its higher water demand (Richard and Cheyrezy, 1995).

The majority of researchers prepared RPC by cement content close to 900 kg/m3. However, some researchers prepared the RPC with cement content less than 900 kg/m3. For example, Tam et al. (2010) and Algburi et al. (2019, b) prepared RPC by cement content of 761 kg/m3 and 880 kg/m3, respectively. Performance of the RPC with cement content less than 900 kg/m^3 for the long-term and structural integrity of civil infrastructure components has to be examined. However, RPC prepared with only silica fume as mineral admixture has been produced with cement content of (761-940) kg/m3 (Richard and Cheyrezy, 1995; Tam et al., 2010; Aydin et al., 2010; Hadi et al., 2017; Algburi et al., 2019, b). Notably, Yigiter et al. (2012) found that RPC can be produced with a significantly reduced cement content of 376 kg/m³ by the partial replacing of cement with Type C fly ash at replacement ratios of up to 60%. However, the adding of fly ash with 60% replacement ratio to the RPC with cement content of 940 kg/m3 and silica fume as mineral admixture decreased the compressive strength from 403 MPa to 338 MPa. The RPC with compressive strength higher than 200 MPa was prepared also by Yunsheng et al. (2008) using a composition of cementitious materials included 40%, 25%, 25% and 10% of Portland cement, ultra-fine slag ultra-fine fly ash and silica fume, respectively.

After Richard and Cheyrezy's (1995) pioneer study, which utilized fine sand with particle sizes between 0.15 mm and 0.6 mm to produce the RPC, the subsequent research has studied the use of fine aggregates with diverse types and particle sizes in preparation of RPC. For example, Yunsheng et al. (2008) utilized fine sand with a maximum particle size of 3 mm, while Yigiter et al. (2012) tested fine aggregates from various sources, including bauxite, granite, and quartz, with particle sizes ranging from 0.4 mm to 3 mm. Sadrekarimi (2004) created lightweight RPC using finely ground quartz sand with particle sizes between 0.125 mm and 0.55 mm. However, Tam et al. (2010) proposed that the ideal particle size for fine aggregates in the RPC has a range falls between 0.15 mm to 0.6 mm.

The above studies highlight that a wide range of fine aggregate sizes and types can be used to produce RPC, depending on the specific application and performance requirements.

The primary function of silica fume in the RPC is to fill the gaps between cement particles, effectively compensating for the lack of coarse aggregate in the mixture. As a result, silica fume enhances the density and homogeneity of the RPC. However, silica fume has also lubricating effect and can produce more hydrated silicates by reacting with lime results from cement (Richard and Cheyrezy, 1995). Undensified silica fume was first employed in the production of the RPC. The slurry form of silica fume was not used because it introduces extra water. This could negatively influence the water/cement ratio of the mixture. In the initial RPC formulations, a silica fume/cement ratio of 25% was utilized. This ratio was determined to offer the best filling performance, effectively occupying the gaps between cement particles and contributing to a denser microstructure. In fact, this dosage was found to be close to that required to fully react with the lime generated during the complete hydration of cement. Nevertheless, cement hydration in RPC mixture is unfinished, and the accessible amount of silica fume is greater than the required amount in the reaction (Richard and Cheyrezy, 1995; Cheyrezy et al., 1995). White-colored undensified silica fume was employed by Sadrekarimi (2004) to develop lightweight RPC with varying proportions of silica fume. The results showed that higher silica fume content reduced the density of the RPC while increasing its compressive strength. In a similar study, Lee and Chisholm (2005) produced RPC using different forms and densities of amorphous or micro silica, all of which significantly influenced the material's strength.

Based on the available studies, silica fume with 25% by weight of cement content is recommended to be used in the RPC mix design. However, the RPC can be produced by replacing the silica fume with other mineral admixtures, which could lead to better environmental impact and durability results.

Various types of superplasticizers have been incorporated into the mix design of RPC. Initially, Richard and Cheyrezy (1995) used a superplasticizer derived from polyacrylate. Later, other varieties such as those based on polycarboxylic ether were also introduced (Menefy, 2007; Malik and Foster, 2010; Hadi et al., 2018 (a)) and modified carboxylate (Lee and Chisholm, 2005; Tam et al., 2010; Algburi et al., 2019, (b)).

The type of water used for conventional concrete, typically potablewater, is also suitable for the RPC. It is important to emphasize that the key components of the RPC such as cement, fine aggregates, silica fume, superplasticizers, and steel fibers are the essential ingredients. However, additional materials like crushed quartz may be recommended in some cases to improve specific properties, but they are not essential for producing the RPC. Also, fibers in RPC cannot be considered a main component as the RPC has been produced without adding of any fiber (Richard and Cheyrezy, 1995; Shaheen and Shrive, 2006; Ju et al., 2007; Al-Tikrite and Hadi, 2017; Algburi et al., 2019 (b)). However, the existence of fiber in RPC is necessary for ductility requirements. Also, the steel fiber has significant influence on the resistance of RPC to shrinkage cracks (Tao et al., 2012).

5. USE OF FIBER IN THE RPC

Use of fibers in the RPC mixture is required due to ductility purposes. Similar to traditional concrete, the commonly used fibers with RPC are the steel fibers. Richard and Cheyrezy (1995) utilized two sizes of steel fibers; 13 mm and 3 mm lengths with diameter of 0.15 mm. The used volume fraction was a range falls between 1.5 and 3 percentages.

Yunsheng et al. (2008) prepared RPC with compressive strength of 200 MPa by using three volume proportions of steel fibers which were 2%, 3%, and 4%. It was found that the RPC with 4% volume fraction of the steel fibers gave higher mechanical properties compared to the RPC with 0%, 2%, 3% volume fraction of the steel fibers.

Ju et al. (2007) examined the influence of volume fraction of the steel fibers on the compressive strength and tensile strength of the RPC. The RPC was produced by adding 1%, 1.5%, 2%, and 3% volume fractions of the steel fibers. The results showed that increasing the volume portion of the steel fibers in the RPC matrix improved the compressive strength and tensile strength of the RPC. The study showed also that RPC having volume portion of 1.5% steel fibers had considerably higher compressive strength and tensile strength than RPC having volume portion of 0% steel fibers.

Al-Tikrite and Hadi (2017) studied the impact of micro steel fibers, industrial deformed steel fibers, and waste steel fibers on the mechanical properties of the RPC. The study showed that RPC reinforced with micro steel fibers had greater strength than RPC containing industrial or waste steel fibers. However, waste steel fibers also improved the strength and ductility of RPC, delivering performance similar to that of RPC with industrial steel fibers.

Based on the results of Algburi et al (2019, b), the RPC contains 1.5% volume fraction of steel fibers had marginally higher compressive strength but significantly higher tensile and shear strength than RPC with 0% volume fraction of steel fibers. However, Richard and Cheyrezy (1995) suggested the optimum proportion of steel fibers in RPC to be 2% by volume or around 156 kg/m^3 to achieve strength and economy requirements.

Recently, Hasan (2024) conducted an experimental study to investigate the proportion influence of industrial and waste tire-steel fibers on the compressive, flexural and impact strength of RPC. The study results revealed that RPC with waste-tire steel fibres has comparable compressive, flexural and impact strength to that of RPC with industrial steel fibers.

Up to now, research on RPC incorporating fibers other than steel fibers is still limited. However, Shaheen and Shrive (2006) explored the use of carbon fibers in RPC by adding 3 mm long carbon fibers at a ratio of 0.125% of the cement weight. They employed accelerated curing AC techniques, including pre-setting pressure, heat treatment, and fog room curing. The carbon fiber-reinforced RPC achieved a compressive strength of approximately 288 MPa, compared to 243 MPa for RPC without fibers.

Canbaz (2014) observed that incorporating polypropylene fibers (13 mm in length) into RPC resulted in a decrease in compressive strength. Specifically, the addition of polypropylene fibers with volume proportions of 0.5% and 1.5% led to reductions in compressive strength of approximately 35% and 25%, respectively.

Sanchayan and Foster (2015) prepared hybrid fiber reinforced RPC contains steel and polyvinyl alcohol (PVA) fibers. Steel fibers were 13 mm long with 0.2 mm diameter, while synthetic PVA fibers were 12 mm long and 0.2 mm diameter. The specimens were cured in hot water. Different proportions of steel and synthetic PVA fibers were used. An average compressive strength between 134 MPa and 170 MPa was obtained. The compressive strength decreased from 144 MPa for the RPC with 0% volume fraction of fibers to 134 MPa for the RPC with 2% volume fraction of synthetic PVA fibers.

Algburi et al. (2019, b) investigated the mechanical properties of 0% fiber-RPC and fiber-reinforced RPC. Three types of fiber were used in that experimental study; steel, steel-glass and glass fibers. Volume fraction of 1.5% for each type of those fibers was used. The steel-reinforced RPC gave higher compressive strength, indirect tensile strength and shear strength than 0% fiber-RPC, steel-glass-fiber-reinforced RPC and glass-fiber-reinforced RPC. The steel-glass-fiber-reinforced RPC and glass-fiber-reinforced RPC had compressive strength marginally lower than that of 0% fiber-RPC, but shear strength higher than that of 0% fiber-RPC.

Xie et al. (2023) examined failure modes of basalt fiber reinforced-RPC using acoustic emission. It was found that basalt fibers with 0.5% and 1% volume fraction can increase compressive strength as well as acoustic energy of RPC.

6. DURABILITY OF THE RPC

The formation of microcracks and porosity within the RPC matrix can be reduced by carefully choosing the raw materials and employing proper curing and compaction methods. This approach results in a more homogeneous consistency and superior durability performance for RPC compared to traditional concrete and even conventional HSC (Fojtik and Hubacek, 2006). Results of Tam et al., (2012) showed that permeability of RPC is lower than that of NSC and its decreased by decreasing the water to binder ratio in the RPC mix.

The performance of RPC in aggressive environments has been examined in numerous of studies. Shin and Yoo (2021) investigated influence of the pre-crack width and exposure period to corrosive environment of sodium chloride on the tensile strength of the RPC. It was found that exposure period up to 20 weeks for pre-cracked RPC specimens did not cause a deterioration and the surface of steel fibers had only minor oxidation. The experimental study of Mao et al. (2020) included production of green-RPC with recycled powder. The results showed that adding recycled powder to the RPC increased resistance of RPC to chlorides attack at late ages.

Impact of external sulfate attack on the RPC with different water to binder ratios and silica fume contents was investigated by Bakhbergen et al (2022). The outcomes of the study indicated that RPC with 0.22 water to binder ratio and 20% silica fume content had superior resistance against external sulfate attack. Wang et al., (2021) examined effect of fly ash and ground granulated blast furnace slag contents on the resistance of the RPC to seawater action. It was found that adding of fly ash and ground granulated blast furnace slag to the RPC clearly enhanced the resistance of the RPC against seawater action and the ground granulated blast furnace slag had better enhancement on the resistance at the late ages. The study results also revealed that the RPC with 20% fly ash and 20% ground granulated blast furnace slag is recommended to be used in terms of workability, durability and strength.

Due to the absence of coarse aggregate, soundness or volume stability of the RPC might be evaluated by the same autoclave expansion standard test adopted for cement mortar. However, Kabir et al., (2020) concluded based on an experimental investigation that autoclave expansion standard test exhibits misleading assessment results for cement used in concrete. The experimental study of Tao et al., (2012) investigated the crack resistance of RPC using the device of restrained ring for shrinkage measurement. The study included an investigation to three factors; volume fraction of steel fiber; sand to binder ratio and water to binder ratio. The results of the study indicated that resistance of the RPC to cracking due to shrinkage mainly depends on the steel fibers content and the optimal volume content of steel fibers to achieve the required cracking resistance is 3%.

Shaheen and Shrive (2006) found that carbon-fiber-reinforced RPC demonstrates a superior behavior against resist freezing and thawing ambiances. Raza and Qureshi (2021) studied the behavior of carbon-fiber-reinforced RPC at high temperature. The study included preparing and testing of 0% fiber RPC, steel-fiber-reinforced RPC, carbon-fiber-reinforced RPC and hybrid steel-carbon-fiber-reinforced RPC. The results of the study showed that hybrid steel-carbon-fiber-reinforced RPC had better behaviour at room and high temperature than steel-fiber-reinforced RPC and carbon-fiber-reinforced RPC. At 800 ºC, the carbon-fiber-reinforced RPC had higher residual compressive, tensile and flexural strength than 0% fiber RPC. Liu and Huang (2009) conducted an experimental study to evaluate the fire resistance of highly flowable RPC without fibers. The study showed that the residual compressive strength of 0% fiber-RPC after fire exposure exceeded that of both NSC and HSC. Also, Canbaz (2014) and Sanchayan and Foster (2015) investigated the fire resistance of RPC and discovered that adding 1% volume fraction of polypropylene or PVA fibers significantly improved its fire endurance and spalling resistance.

Yi et al., (2012) examined the blast resistance of RPC and ultra-high-strength-concrete compared to that of NSC. The blast resistance was measured using specimens with dimensions of (1000 × 1000 × 150) mm. The experimental program included applying blast tests with charge of a 15.88 kg Ammonium Nitrate-Fuel Oil (ANFO), blast distance of a 1.5 m and a strain rate for the blast load of 278–457 s^{-1}. The authors found that specimens of RPC and ultra-high-strength-concrete had superior blast resistance and failure modes against explosion compared to NSC specimens. The ultra-high-strength concrete and the RPC had superior mechanical properties (compressive strength, tensile strength, flexural strength, modulus of elasticity and Poisson's ratio) compared to the NSC. Together with the higher mechanical properties, the presence of reinforcing steel bars within the ultra-high-strength concrete specimens and the steel fibers within the RPC specimens prevented the brittle failure and achieved the required ductility with the absorption energy to control cracks resulting from blast load. In addition, the RPC exhibited more flexible behavior and had greater capacity for the absorbing energy against the blast load compared to the ultra-high-strength concrete. Yalcinkaya et al., (2014) recommended use of RPC in structures which are subjected to abrasion effect. Consequently, the studies revealed that the RPC generally has better durability than NSC.

7. APPLICATIONS AND EXPERIMENTAL STUDIES OF THE RPC

Reactive Powder Concrete (RPC) has been effectively implemented in various civil infrastructure projects across the globe. Its first notable use was in a filled steel tube composite footbridge in Sherbrooke, Canada Fig. 2, a (Malik, 2007). The RPC was also used to construct the foundation of a condensation building for a cooling tower at the Cattenom power station in France (Fojtik and Hubacek, 2006). Following this, RPC was adopted for building footbridges in Japan and South Korea, as well as a 175-meter-span footbridge in New Zealand. A significant milestone was the construction of the Shepherds Creek bridge Fig. 2, b in Australia, which spans 15 meters and is 21 meters wide, marking it as the world's first highway traffic bridge built with RPC.

(a) (b)

Fig. 2. a: Sherbrooke footbridge and b: Shepherds Creek bridge

One of the most important applications for the RPC is the Qinghai-Tibet railway bridge Fig. 3,a in China with an altitude greater than 4,000 meters (above sea level). The length of the railway was 576 km and it was built on frozen earth. The RPC was used efficiently in the construction of the sidewalk of the railway bridge (Wen-yu et al., 2004).


(a) (b)

Fig. 3. a: Qinghai-Tibet railway bridge and b: building of the Central Bank in Iraq

Due to its excellent durability, the U.S. Army Corps of Engineers proposed the use of RPC for producing sewer systems, culverts, and pressure pipes (Campbell and O'Neil, 1998). Consequently, precast-stressed high-voltage columns, pressure pipelines, and drainage pipes made from RPC have been developed and manufactured in the United States. (Fojtik and Hubacek, 2006). Yan (2009) studied the feasibility of using the RPC for construction of barriers in highways. The study showed that RPC barriers can be effectively used in highways due to durability and economic reasons.

Other applications of the RPC are the elevation of the Bus Center in Thiais France, roofing for the railway station in Calgary and the innovative cladding system of the high rise building (Denisiewicz and Kuczma, 2013). In fact, the cladding for the building of the Central Bank in Iraq Fig. 3, b which is still under construction seems to be constructed from a special type of HPC could be called a glass fiber reinforced RPC (DAAX, 2022).

After the pioneer experimental work of Richard and Cheyrezy (1995), many studies have been conducted to produce structural members with RPC. This study however, focuses on the studies of RPC columns and use of RPC as strengthening material. The authors assumed that these are the most available important studies about the RPC used in structural members.

The superior compressive strength of RPC compared to the other types of concrete, gave the motivation for the researchers to study the use of RPC in columns. Malik and Foster (2010) conducted an experimental study on circular RPC column specimens wrapped with carbon fiber reinforced polymer (CFRP). The study reported that the CFRP-confined RPC column specimen had axial strength 19% higher than that of the unconfined column specimen.

Huynh et al., (2015) studied the behavior of square RC column specimens fabricated by HSC core with RPC ring and tested under three-point loading. The results of the study revealed that adding of the RPC around the HSC core enhanced the strength and the energy absorption of the column specimens.

Hadi et al., (2018, b) investigated the behavior of hollow circular RPC column specimens confined with CFRP tubes. The results of the study showed that confinement of CFRP tubes increased ductility of the specimens. Wang et al., (2019) studied experimentally the behavior of RPC-filled steel tube columns. The study outcomes revealed that confinement of steel tubes increased the axial load capacity of the RPC core.

Shan et al., (2021) proposed a new column with section consists of RPC ring and NSC core. Those columns were tested under cyclic load and exhibited higher initial stiffness and lateral displacement capacity compared to the reference columns.

Makki and Naji (2022) examined the experimental behavior of RPC columns with and without steel fibres. The study included preparation and testing of RPC column specimens with 0% and 2% volume fraction of steel fibres. The results of the study indicated that increase the steel fibers volume fraction from 0% to 2% caused an increase in the ultimate axial load of the column specimens.

The key characteristics of any material used for repairing or retrofitting concrete members are its bonding ability and deformation capacity to withstand stresses caused by differential shrinkage (Lukovic et al., 2012). The RPC possesses a dense a dense microstructure composed of finely graded particles that compact efficiently (Malik and Foster, 2010). The inclusion of steel fibers enhances the ductility and energy absorption capacity of RPC (Richard and Cheyrezy, 1995). These properties help reduce differential tensile strain in RPC and improve its load-carrying capacity (Malik and Foster, 2010).

The RPC was found to be an excellent repairing material and had the potential to strengthen cylinder and prism specimens for compressive and flexural strength after exposure to hazardous conditions. The RPC showed higher bond strength, dynamic modulus of elasticity and bond durability than NSC and high strength mortar (Chang et al., 2009; Lee et al., 2007).

Hadi et al., (2018, a) and Algburi et al. (2019, a) investigated the behavior of RC circular and square column specimens strengthened with RPC jacket and CFRP wraps Fig.3. The specimens were tested under concentric and eccentric axial loads as well as under four-point bending. The experimental results showed that the RPC is an effective strengthening and shape modification material for the circular and square RC columns, respectively. Strengthening of the RC columns with RPC jacketing and CFRP wrapping is considered new strengthening technique. In this technique, the ultimate load and absorption energy of the column under different loading conditions increase significantly due to the crucial increase in stiffness of the column by the RPC jacketing. The CFRP wrapping for the jacketed column not only achieves more enhancement in the ultimate load by confinement effect but also increases ductility and absorption energy of the jacketed column.

Fig. 4. Column specimens strengthened with RPC jacket and CFRP wraps (Hadi et al., 2018, a and Algburi et al. 2019, a)

8. CONCLUSIONS

The aim of this study is to present a comprehensive effectively summarized review about the RPC. The review resulted in the following conclusions:

1. The RPC is a superior category of HPC primarily consists of cement, silica fume, fine aggregate, water and superplasticizer. For ductility requirements, steel fibers are added to the RPC mix.

2. NC-RPC achieved compressive strength between 84 and 212 MPa, whereas compressive strength higher than 212 MPa for the RPC cannot be achieved without applying one of the AC techniques.

3. The RPC has been prepared with cement content up to 940 kg/m^3. However, RPC with cement content of only 761 kg/m^3 has been prepared too.

4. Fine aggregate with size not greater than 6 mm has been used to produce the RPC. Nevertheless, the content, size and type of the fine aggregate in RPC need to be considered for the different applications.

5. Densified and undensified silica fume as well as micro and amorphous silica have been used in production of the RPC. Silica fume with 25% by weight of cement content is found to be recommended in production of the RPC. However, production of the RPC with other mineral admixtures may lead to better environmental impact and durability results.

6. Superplasticizer with polyacrylate, polycarboxylic ether and modified carboxylate origin have been used to produce the RPC.

7. Steel fiber with 156 kg per cubic meter is recommended to be used with RPC.

8. Carbon fiber, glass fiber, and polypropylene or PVA fibers have been proposed to enhance resistance of the RPC to freezing-thawing, corrosion and fire, respectively.
9. Durability of the RPC was found to be better than durability of NSC in terms of permeability, sulfate-chloride attacks and blast-abrasion resistance.
10. The RPC has been used in construction of civil infrastructure parts worldwide such as foot bridges, highway bridges, power stations, pipes, culverts and cladding of high rise buildings.
11. Experimental studies proposed the RPC to be used in columns such as CFRP-confined RPC columns, CFRP tubes-confined hollow circular RPC columns, RPC-filled steel tube columns and composite column constructed from RPC ring and NSC or HSC core.
12. The RPC jacketing plus CFRP wrapping was found to be an innovative technique to be used for strengthening of RC columns.

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