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Reactive Powder Concrete (RPC)

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❖ ABSTRACT

The term Reactive Powder Concrete (RPC) has been used to describe a fibre reinforced , superplasticized, silica fume-cement mixture with very low water-cement ratio, characterized by the presence of very fine aggregates instead of ordinary aggregate.

Fibres are incorporated in RPC in order to enhance the fracture properties of the composite material.

Reactive powder concrete, is recognised as a revolutionary material that provides a combination of ultra-high

strength and excellent durability.

Reactive Powder Concrete (RPC) is catching more attention now days because of its high mechanical and durability characteristics. RPC mainly comprises of cement, silica fume, silica sand, quartz powder and steel fibers. A comparison of the physical, mechanical, and durability properties of RPC and High Performance Concrete shows that RPC possesses better strength both compressive and flexural and lower permeability compared to High Performance Concrete. RPC will allow the concrete industry to optimize material use, generates economic benefits, and build structures that are strong and durable.

Keywords— RPC, Silica fume, steel fibers,Compressive strength, Workability**.**

❖ INTRODUCTION

Reactive powder concrete (RPC) is ultra-high strength and high ductile composite material with advanced mechanical properties. Reactive powder concrete is a concrete without coarse aggregate, but contains cement, silica fume, sand, quartz powder, super plasticizer and steel fiber with very low water binder ratio. The absence of coarse aggregate was considered by inventors to be key aspect for the microstructure and performance of RPC in order to reduce the heterogeneity between cement matrix and aggregate.
The concept of reactive powder concrete was first developed by P. Richard and M. Cheyrezy and RPC was first produced in the early 1990s by researchers at Bouygues laboratory in France. The world's first Reactive Powder Concrete structure, the Sherbrooke Bridge in Canada, was erected in July 1997. The addition of supplementary material, elimination of coarse aggregates, very low water/binder ratio, additional fine steel fibers, heat curing and application of pressure before and during setting were the basic concepts on which it was developed.There is a growing use of RPC owing to the outstanding mechanical properties and durability. RPC structural elements can resist chemical attack, impact loading from vehicles and vessels, and sudden kinetic loading due to earthquakes. Ultra-high performance is the most important characteristic of RPC. RPC is composed of more compact and arranged hydrates. The microstructure is optimized by precise gradation of all particles in the mix to yield maximum density. It uses extensively the pozzolanic properties of highly refined silica fume and optimization of the Portland cement chemistry to produce highest strength hydrates.

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- **Advantages of RPC**

- Used in areas where weight savings is required.
- Low porosity
- Impermeable
- Replace steel in compression members
- Limited shrinkage
- Increased corrosion resistance
- No penetration of liquid or gas
- Improved seismic performance

- **Limitations of RPC**

In a typical RPC mixture design, the least costly components of conventional concrete are basically eliminated or replaced by more expensive elements. The fine sand used in RPC becomes equivalent to the coarse aggregate of conventional concrete, the Portland cement plays the role of the fine aggregate and the silica fume that of the cement. The mineral component optimization alone results in a substantial increase in cost over and above that of conventional concrete (5 to 10 times higher than HPC). RPC should be used in areas where substantial weight savings can be realized and where some of the remarkable characteristics of the material can be fully utilized. Owing to its high durability, RPC can even replace steel in compression members where durability issues are at stake (e.g. in marine condition). Since RPC is in its developing stage, the long-term properties are not known.

❖ RESEARCH ON RPC

(Richard et al. 1995) conducted research aimed at the development of an ultra-high strength ductile concrete. Their study lead to the development of reactive powder concrete (RPC). Reactive powder concrete has compressive strength ranging from 200MPa to a maximum of 810MPa. RPC can be fibered or non-fibered. Steel fibers were incorporated to improve tensile strength and ductility. A detailed analysis of the approach adopted for enhancement of the homogeneity and compacted density of RPC concretes was described in the paper.

(Lee et al. 2007) made a study on RPC as a new repair material and evaluate its bond durability to existing concrete.

Freeze–thaw cycle acceleration deterioration test, was selected for the evaluation of bond durability of the repair materials. The samples were evaluated by the compressive strength, bond strength (slant shear test), steel pull out strength, and relative dynamic modulus NDT tests before and after aging. The test results showed that the RPC displayed excellent repair and retrofit potentials on compressive and flexure strengthening and possesses high bond strength, dynamic modulus and bond durability as compared with other concretes. The adhesion between the RPC and the steel was much greater than that for other concretes.

(Zheng et al. 2013) studied the effect of temperature on the compressive and tensile properties of reactive powder concrete. They examined the effect of temperature, steel fiber content, hold time, dimension of specimens and explosive spalling in the temperature range of 200 °C – 800 °C. There was a decrease in cube compressive strength at 100 °C, increase at temperatures from 200 to 500 °C, and decrease at temperatures above 600 °C. As the fiber content increased, below 300 °C, the cube compressive strength of RPC increased, but decreased above 300 °C as the fiber content increased. The tensile strength of RPC with steel fibers decreased at temperatures below 200 °C, increased at temperatures ranging from 200 to 300 °C, and decreased at temperatures above 300 °C. The results indicated that 2% steel fibers (volume content) can prevent explosive spalling of RPC and significantly enhance the compressive and tensile strengths. (Liu and Huang 2009) studied the fire performance of highly flowable reactive powder concrete. By conducting a series of fire endurance temperature tests and fire duration tests, it was found that the residual compressive strength of RPC decreased with increase in fire duration. As compared to high performance concrete (HPC) and ordinary concrete (OC), the studied RPC not only had a higher fire endurance temperature but also possessed a larger residual compressive strength after fire. In addition, the experimental results of thermogravimetric analyses on RPC, HPC and OC specimens suffered from the same fire temperature and duration indicated that the total weight loss of RPC was lower than others.

(Kushartomo et al. 2015) made a study on the Mechanical behavior of reactive powder concrete with glass powder substitute. The Reactive Powder Concrete (RPC) with quartz powder substitute has a high compressive strength of 180 MPa and has a fairly high tensile strength. That research used the RPC with quartz powder to cement ratio of 30% and steam curing technique in an autoclave temperature of 250ºC. Concerning the use of local and recycled material, in this paper, the quartz powder is substituted by glass powder from the waste glass shards material of housing industry. The objective of the study was to investigate the influence of glass powder in the mechanical behavior of RPC. The mechanical behavior was examined by the tests of compressive strength, flexural strength and split tensile strength. The RPC used glass powder that grained to micron meter size with the content as much as 10%, 20%, and 30% of cement mass, and the maximum temperature of steam curing is 95ºC. The results indicated that the use of glass powder was good enough to replace quartz powder in RPC. The maximum compressive strength value achieved was 136 MPa for the RPC with the glass powder content of 20%. The RPC with glass powder of 20% indicated a maximum of average of split tensile strength value of 17.8 MPa and the average of flexural strength value of 23.2 MPa.

(Yanzhou et al. 2015) conducted experiments to study the properties and microstructure of reactive powder concrete having a high content of phosphorous slag powder and silica fume. Reactive powder concrete (RPC) specimens containing phosphorous slag powder (PS) and silica fume was about 50% (by the weight of binder) were produced after they had been cured in 95oC steam for a given duration. The test results of strength (compressive and flexural), freeze–thaw and sulfate resistance verified an excellent mechanical and durability properties of RPC containing a high content of PS. The investigation of selected RPC compositions by Thermogravimetric Analysis, Mercury Intrusion Porosimetry and Scanning Electronic Microscope made it possible to better understand their mechanical and durability properties based on their microstructure. Mercury porosimetry results indicated that RPC had very low porosity and the diameter of the most probable pore was less than 10 nm.

(Canbaz 2014) studied the effect of high temperature on reactive powder concrete. The properties of RPC with different plastic fiber ratios were investigated at different temperatures. Samples with the dimensions 7cmx7cmx7cm were produced using CEM I 52.5 R cement, quartz sand, quartz powder, silica fume, steel wire, a superplasticizer, polypropylene fibers, and water. To achieve high strength the specimens were subjected to compression after casting and accelerated curing. After the curing, the concrete was exposed to temperatures of 20, 100, 400, 700, and 900 ºC for 3 h. A cooling regime was applied to the air after the heating process. Compressive strength, unit weight, and ultrasonic pulsevelocity tests were performed. Compressive strengths higher than 200 MPa were achieved after water curing at 90 ºC for 3 days and after applying a pre-setting pressure of 80 MPa to RPC. The addition of polypropylene fiber caused a maximum reduction in strength of 140 MPa. A strength of 165 MPa was obtained in the case of 1% fiber ratio. The variation in the fiber ratio caused a decrease in strength. The unit weight of ordinary concrete was 2.4 kg/dm3, whereas the average unit weight of RPC was 2.75 kg/dm3. The UPV decreased to 10% with the utilization of polypropylene fiber in the RPC. Based on the results of this study, the addition of 1% polypropylene fiber in RPC and curing temperatures below 400oC are recommended.

(Ahmad et al. 2015) examined the effect of key factors, which affected the performance of reactive powder concrete (RPC) mixtures. An optimum sand grading was selected based on the maximum compressive strength and acceptable flow of a typical RPC mixture keeping the proportions of its ingredients constant. The sand grading and fiber content were kept constant at their optimum levels, and a total of 27 mixtures of RPC were selected for study by considering three levels of the three key factors namely water-to-binder ratio, cement content and silica fume content, according to a 33 factorial experiment design. The dosage of superplasticizer for each mixture wasoptimized and the flow was kept in the desirable range of 180– 220 mm. The performance of the selected mixtures of RPC were evaluated in terms of compressive strength, modulus of rupture and modulus of elasticity. Statistical analysis of the experimental data showed the significant effect of sand grading, water-to binder ratio, cement content and silica fume content on flowability and mechanical properties of RPC. (Helmi et al. 2016) presented the effect of treatments (static pressure of 8 MPa and heat curing at 240 ºC for 48 hours) on microstructure formation. Results indicated that pressure decreased the total pore volume and increased the capillary pore volume due to the movement of grains. The space createdcould allow additional C–S–H growth during hydration. Heat treatment accelerated the propagation of micro cracks due to thermal expansion of the solid phases, volumetric expansion of the air and increased pressure within entrapped voids. It induced further crystalline hydrate formation inside the capillary pore network. Pressure followed by heat curing treatment increased the capillary pore volume and then accelerated both the hydration and pozzolonic reactions with subsequent increased in skeletal density.

(Zdeb 2015) presented an analysis of mechanical properties and microstructure of reactive powder concretes RPC manufactured with the use of three different industrial Portland cements diversified in terms of the strength class, chemical and mineral composition as well as specific surface area. The developed materials were subjected to three different hydrothermal curing conditions. The test results showed that the factors most influencing the consistency of the concrete mixture were the chemical and mineralogical composition of the binder. It appeared that when it comes to mechanical properties, the factor which plays the crucial role was the specific surface area of cement. For one of the analyzed cements, it was possible to limit the value of W/B ratio up to 0.17, without adversely affecting the properties of the concretemixture.

(Zhu et al. 2016) conducted investigation on using recycled powder from waste of clay bricks and cement solids in reactivepowder concrete. Recycled powder, produced from the construction and demolition wastes, contains unhydrated cement particles. It reduces environment pollution to use recycled powder as a cementing material. It was studied to use recycled powder to partially replace silica fume or cement in Reactive Powder Concrete (RPC) to develop environmentally- friendly and cost-saving RPC mixture with high performance. Properties of the recycled powder were tested. According to maximum packing theory, the RPC mix with the recycled powder was designed. Influences of the fine aggregate, quartz and natural sand, on the RPC were investigated. The water-cementitious materials ratio (w/cm) for RPC mixes with the recycled powder were studied and selected. The recycled powder was used to replace the silica fume and cement in RPC respectively, and influences of the replacement ratio on the flowability, strength and durability were investigated. The standard curing was used for all the tests instead of steam curing normally required for RPC. Considering the flowability, strength, durability, cost and environmental savings, it was suggested that the recycled powder can be usedto replace the silica fume and cement in RPC partially, and natural sand can be used instead of quartz. Additionally, influences of GGBFS powder on RPC mix with the recycled powder were investigated.

(Bae et al. 2016) investigated the bond stress between steel-fiber-reinforced reactive powder concrete (SFRPC) and conventional reinforcement to determine specific values for design bond stress. Test results were compared with

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previously suggested analysis methods. Tests were carried out using the direct pull-out test. The main variables were compressive strength of the concrete, concrete cover, and inclusion ratio of steel fiber. The increase rate of ultimate bond stress between SF-RPC and conventional reinforcement was decreased although the ultimate bond stress was increased with increasing compressive strength of the SF-RPC matrix. The effect of the concrete cover on ultimate bond stress and itsincrease rate was similar to that of the compressive strength of concrete. However, an even more significant change was observed with change in concrete cover. They also observed an effect of steel fiber inclusion. Inclusion of a 1% volume fraction of steel fiber increased the ultimate bond stress by two times the bond stress between the plain RPC matrix and conventional reinforcement. However, a 2% steel fiber volume fraction did not increase the ultimate bond stress significantly. In order to obtain safety for bond design of SF-RPC precast members, previously suggested analysis methods for ultimate bond stress and empirical equations for ultimate bond stress were evaluated.

(N. Roux 1996) conducted an experimental study on durability of reactive powder concretes. The durability of reactive powder concretes (RPC) had been defined by measuring porosity, air permeability, water absorption, diffusion, and migration of chloride ions, accelerated carbonation, resistance to reinforcement corrosion, resistivity, and resistance to mechanical abrasion. Results were compared with the characteristics of a grade 30 MPa concrete with a low cement content and a grade 80 MPa very high performance concrete. The RPC displayed excellent granular compactness, and its low water content helped reduce porosity. That resulted in an excellent resistance to the penetration of aggressive agents with respect to the reference concretes, and structures built with RPC were expected to significantly outlast those built with ordinary concrete. The extremely high resistance of RPC200 concrete to the penetration of aggressive agents corresponded to excellent durability characteristics, thus yielded a significant increase in the life expectancy of structures built with reactive powder concretes.

(Agharde and Bhalchandra 2015) studied the mechanical properties of reactive powder concrete made by using fly ash. The main objective of the study was to check the effect of replacing silica fume by fly ash and percentage variation of steel fiber on reactive powder concrete, to achieve economy without any significant change in properties of RPC. The silicafume was replaced by fly ash by its weight variation of 0% to 50% with interval of 10 %. It was found that replacement of fly ash up to 40% by silica fume was economical to achieve high compressive strength up to 90 MPa under normal curing. Percentage of fiber content varied from 0 % to 1 % with interval of 0.25%. It was found that addition of 0.75 percentage of fibers content gave better flexural and tensile strength.

(Faizan Akbar, Fawad Bilal 2015) optimized mix proportions for reactive powder concrete and investigated the compressive strength. The specimens were tested for the compressive strength so as to get optimized mix design that would deliver the maximum performance in terms of compressive strength. A total of 54 cubes 3x3x3 inches were prepared. Specimens were treated with normal water as well as with hot water. The content of ingredients as well as the w-b ratio was also kept changing, so as to get a better understanding. Results showed that the mix proportions with higher silica content and lower water-cement ratio delivered good results.

(Mostofinejad et al. 2016) made a study on determination of optimized mix design and curing conditions of reactive powder concrete. The study investigated the compressive strength of non-steel microfiber reinforced RPC by utilizing different mix designs under various curing conditions to determine the optimal practical conditions and parameters that would lead to maximum RPC compressive strength. Results revealed that the eight-step procedure employed in the study considerably enhanced the compressive strength of the specimens about 174% as evidenced by the rise in from 85MPa (28 days) to 233MPa (13 days). Furthermore, different curing treatments were applied and results showed the combined curing treatment, including 3 days of autoclave curing treatment at 125 ºC followed by 7 days of heat cure treatment at 220 ºC represented more effective performance due to resulted superior mechanical properties at a minimum curing time.

(M K Maroliya 2012) did an investigation on reactive powder concrete containing steel fibers and fly- ash. They studied the effect of water to cement ratio, curing conditions, compositions and the effect of mineral and chemical admixtures to achieve higher compressive strength. Compressive strength test and flexural strength test were conducted. The results showed that silica fume gave better compressive strength and good flow at lower water/cement ratio. Partial replacement of silica fume by fly ash and metakaolin did not help much to increase strength but from cost aspect it can be justified.

(Maroliya 2012) studied the bond strength of reactive powder concrete containing steel fiber and silica fume. RPC was studied by conducting direct pull out test of reinforcement specimen. Results showed that pull out behavior of plain matrix was perfectly of brittle nature whereas RPC with fibers maintained the load carrying capacity with large deformation and prevented splitting cracking and disintegration of matrix. The behavior of RPC under different curing condition was alsostudied.

❖ APPLICATIONS OF RPC

The following are the various applications of reactive powderconcrete.

- Impact-resistant structures
- Nuclear structures
- Skyscrapers
- Corrosion-proof structures
- Pavements
- Barrier to nuclear radiation.
- Security for banks, computer centers
- Pedestrian Bridge 197m span, 3.3m wide, 3.0m

deep, 30mm thick slab, in the city of Sherbrooke, Quebec, Canada.

- Seonyu foot Bridge 120m span, 4.4m wide, 1.3m deep, 30mm thick slab, in Seoul, Korea
- Sakata Mirai footbridge, in Japan
- Sewer, Culvert and pressure pipes in Army engineer waterways experiment station, Viksburg, MS.
- Isolation and containment of nuclear waste of severalprojects in Europe.
- Half-canopy in steel form of Shawnessy Light RailTransit Station, Calgary, Canada

❖ CONCLUSION

RPC is an emerging technology that lends a new dimension to the term ‒high performance concrete. It has immense potential in construction due to superior mechanical and durability properties than conventional high performance concrete, and could even replace steel in some applications. The development of RPC is based on the application of some basic principles to achieve enhanced homogeneity, very good workability, high compaction, improved microstructure and high ductility. RPC has an ultra-dense microstructure, giving advantageous waterproofing and durability characteristics. It could, therefore be a suitable choice for industrial and nuclear waste storage facilities.

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