MIX DESIGN, MECHANICAL PROPERTIES, AND IMPACT RESISTANCE OF REACTIVE POWDER CONCRETE (RPC)

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Abstract

High performance concretes with compressive strengths of 100 to 120 MPa have been developed and are being increasingly used for the construction of structural elements. More recently, Reactive Powder Concretes (RPCs) have been developed which have enhanced homogeneity (by the elimination of coarse aggregates and the replacement of natural sand with very fine quartz sand), enhanced microstructure (by the use of a high dosage of silica fume and post-set heat-treating), and enhanced ductility (by the incorporation of small specially developed steel fibers. In order to determine guidelines for the production of RPCs the effects of the following parameters on fresh and/or hardened properties have been determined: (a) superplasticizers obtained from different suppliers, (b) water-binder ratio, (c) quartz sand grading, (d) silica fume content, (e) ternary blends, i.e. pulverised fly ash or ground granulated blast furnace slag in combination with silica fume, and (f) volume and type of fibers. Tests on the mechanical properties indicate that RPC has enhanced tensile strength and ductility, i.e. flexural strengths are likely to be between 30 and 60 MPa and fracture energies above 10000J/m². Initial results from simple impact load tests, without instrumentation, on 1000mm square x 100mm thick unreinforced slab supported on all sides, were very encouraging; the concrete at the top powdered under repeated impacts but there was no indication of tensile cracking. A cone of concrete sheared off from the underside of the slab after about 70 impacts when the thickness of the slab had been reduced considerably by the powdering on the top surface.

Key words: High performance fiber reinforced cementitious composites (HPF RCC), reactive powder concrete (RPC), pulverised fly ash (pfa), silica fume, compressive and flexural strength, impact load.
1. INTRODUCTION

Concretes with compressive strengths of 100 to 120MPa have been developed and are being used for the construction of structural elements [1,2]. Concrete with compressive strength of 250-300MPa can also be produced using different techniques such as:

- Compact granular matrix concretes (DSP) with high superplasticizer and silica fume content, also incorporating ultra-hard aggregate (calcinated bauxite or granite)[3].
- Macro Defect Free (MDF) polymer pastes [4] which have very high strength (150MPa or more), in particular when mixed with aluminous cements [5].

An answer to the problem of the low ductility of the cementitious matrices obtained with these various techniques, was found with the incorporation of steel fibers. Thus the Slurry Infiltrated Fiber Concrete (SIFCON) technique [6] involves filling the formwork with bulk fibers, and injecting a fluid mortar slurry. SIFCON, although an interesting material, has had only limited industrial applications because of the difficulties in placing it. Nonetheless, the above techniques have provided a basis for the development of a number of similar or derivative materials in different parts of the world. One such group of materials is the ultra high performance fiber reinforced concretes (UHPFRCs) which have been developed to improve the mechanical performance of cementitious materials, especially strength and ductility under tension [7]. Examples of commercial UHPFRCs are (a) Compact Reinforced Composites (CRC) developed by Aalborg Portland in Denmark, (b) BSI developed by Eiffage group in France, (c) Reactive Powder Concrete (RPC) developed by Bouygues in France, (d) Multi-Scale Fiber-Reinforced Concrete (MSFRC) developed by Laboratoire Central des Ponts et Chaussees in France, and (e) Ductal developed by Lafarge, Bouygues and Rhodia in France. Typical composition of UHPFRC is as follows: A very low water-cementitious ratio ranging from 0.16 to 0.24 achieved by using high cement content (955kg/m³) and a high silica fume content (240kg/m³) and a high dosage of a superplasticiser (15 litres/m³). The only “aggregate” used is fine (150-400 µm) quartz sand (1050kg/m³). A high percentage by volume (2.5 to 10%) of special types of steel fibers (24 or 12 mm length and 0.16mm in diameter) are used. Combinations of short and long fibers in “cocktails” incorporating polypropylene fibers have also been used. The basic principles in the selection of the above materials for the production of these UHPFCs are:

- Enhancement of homogeneity by elimination of coarse aggregate,
- Enhancement of compacted density by optimization of the granular mixture, i.e. the reason for the high silica fume content and use of fine quartz sand as the only aggregate,
- Optional enhancement of the microstructure by post-set heat-treating, i.e. the quartz sand may become reactive at these elevated temperatures,
- Enhancement of ductility by incorporating small-sized steel fibers,
- Maintaining mixing and casting procedures as close as possible to existing practice for normal and high strength concretes.
Application of the first three principles produces a matrix with very high compressive strength, but with ductility no better than that of conventional mortar. The inclusion of fibers improves tensile strength, and also makes it possible to obtain the required level of ductility. Measures relating to composition (homogeneity and granular compacted density) are the basis of the RPC concept, and are applied in all cases. Application of post-set heat-curing appears to be an optional measure designed to enhance performance. The advisability of applying these measures must be assessed for each RPC application, according to the technological difficulties involved and/or their cost (heat-treatment). The compressive strengths of RPCs are likely to be between 170 to 230 MPa depending on the post-set heat treatment (20 to 90°C). Values for flexural strengths are likely to be between 30 and 60 MPa, fracture energies above 10,000 J/m² and moduli of elasticity between 50 to 60 GPa. RPC appears to be a promising new material not only because of its enhanced ductility but also because the mixing and casting procedures are no different to existing procedures for normal and high strength concretes. RPC has, however, a substantial increase in cost over and above that of conventional and even high performance concrete and it is therefore appropriate to identify applications which fully utilize RPC’s mechanical properties and performance characteristics. Research therefore needs to be conducted to develop, and facilitate commercialisation of, precast products which utilize many of the enhanced properties of RPC.

The main applications of RPC up till now have been:

- Construction of prestressed structures without any steel reinforcement. The Sherbrooke Footbridge in Canada was the first structure to be built with RPC [8] using a mix developed by the University of Sherbrooke (Canada). The use of RPC in structures comes up against the lack of design rules allowing full advantage to be taken of the improved mechanical characteristics of the material and of its ability to be used without passive reinforcement. Following a performance assessment, BSI (another type of UHPFRC) has been adopted by the French Ministry of Transport and its Roads Department for construction of two raised sections of motorway close to the city of Valence in the Drome Region [9].
- Pipe products for the conveyance of water, sewage and other liquids under pressure or gravity flow provide an opportunity to utilize many of the enhanced properties of RPC [10]. The USA Army Corps of Engineers has developed (1994-1997) pipe prototypes which exhibit greater overall value than pipes fabricated from other materials.

Based on the mechanical properties of RPC it would also appear to be attractive for construction of security enclosures, such as safes and computer centres, nuclear waste containment vessels, and defense structures; applications that require high impact resistance. The interest for these new concretes appears to have been mainly in France, Canada and USA.

2 AIMS AND OBJECTIVES OF PROJECT

The University of Liverpool was approached by Hamber Safes Ltd. (UK) to assist with: (a) determining guidelines for the production (selection of materials and mix
proportions, and curing regimes) of RPCs and (b) investigating the impact load resistance of RPC in order to determine its suitability for use in the construction of security enclosures and more specifically safes.

3 MATERIALS AND EXPERIMENTAL PROCEDURES

The work is divided into two series of concrete mixtures. Initial work aimed at developing a workable concrete mixture with compressive strengths of around 200MPa. Once this was achieved, sixteen variations of this mixture were cast to optimise/improve its mix proportions and mechanical properties.

3.1 Materials

Single batches of portland cement, pfa, and ggbs were used throughout. Silica fume in the undensified form was used for Series I mixtures while the densified form, but from the same supplier, was used for Series II. The aggregate used was a silica sand with particle sizes less than 400 µm (79% passing the 300 µm sieve). The superplasticizers used were a naphthalene based one and two polycarboxylate polymers – powder and liquid form. The fibers were 12mm in length and 0.16mm in diameter. Ground glass cullet was obtained from two sources – one was coarser than the silica sand and the other one was fine enough to be considered a powder.

3.2 Mixing, Casting, Curing And Testing of Concrete Specimens

The materials were weighed and placed in a 0.01m³ or 0.02m³ capacity horizontal pan mixer in the order: cement, microsilica, silica fume, pfa or ggbs, and silica sand. The materials were first dry mixed and the water and superplasticizer, previously mixed together, were added to the rotating drum. When fibers were used, these were added slowly to the rotating drum after the rest of the materials had been properly mixed and the concrete had a “wet” appearance. The concrete was mixed for 5 minutes and then cast into (a) either 75mm or 100mm steel cube moulds for compression tests, (b) 160 x 40 x 40 mm or 100 x 100 x 500mm steel prism moulds for flexural strength, and, (c) 300 mm height x 150 mm diameter cylinder moulds for modulus of elasticity tests. All the specimens were then compacted on a vibrating table and subsequently covered with a damp hessian and a polythene sheet. They were demoulded at 1-day, or as soon as the concrete had set, and placed either in a curing tank whose temperature was set at 20°C or wrapped in wet hessian and polythene sheet and placed in an oven at 90°C. The majority of these were subsequently tested for compressive strength at 7, 14 and 28-days.

4 RESULTS AND DISCUSSION

4.1 Series 1 – Preliminary tests including impact loading assessment

The first series aimed at investigating the ease with which Reactive Powder Concrete with a compressive strength of 200 MPa could be made in the laboratory with mix proportions similar to those used elsewhere, i.e. 955 kg/m³ of cement, 240 kg/m³ of silica fume, 1050 kg/m³ of silica sand, 210 kg/m³ of water, 61 litres/m³ of...
superplasticiser and 190 kg/m$^3$ of steel fibers. Three types of superplasticisers, a naphthalene based and polycarboxylate polymer in powder form and liquid form, were tried to see the lowest water-binder ratio possible with the materials being used. The polycarboxylate polymers proved to be more efficient than the naphthalene based polymer. An attempt was made to improve the workability of the concrete by overdosing the mix with the powder polycarboxylate polymer. The workability did not improve significantly, indicating that adsorption of the superplasticiser on the surface of the cement and silica fume surfaces had reached saturation value. This also caused excessive retardation and the cubes could only be demoulded six days after casting. The late application of post-set heat treatment resulted in slightly lower strengths, i.e. 165 MPa, than cubes cast with the liquid form of superplasticiser, i.e. 200 MPa, that had been demoulded a day after casting and then cured at the elevated temperature of 90°C. The flexural strengths of two specimens cast from the final mix were determined to be 37 and 45 MPa. The tests were carried out using constant deflection rate as measured by the load platen which did not prove to be very accurate as can be seen by the initial curve in the stress-deflection graph, see Figure 1. Nonetheless the initial results obtained show the ductile behaviour of RPC; removing the load and reloading the specimens still indicated a residual flexural strength of 20.5 and 25 MPa despite that the specimens were cracked. The fibers held the two cracked parts together, see Figures 2 and 3.

![Figure 1: Flexural Stress versus Deflection.](image)
The modulus of elasticity was determined to be 45 GPa which is on the high side for normal and high strength concretes (usually in the range 35 to 45 GPa). The value obtained is however lower than that predicted from the expression for the secant modulus of elasticity of concrete, $E_c$ (GPa), recommended by ACI 318-89 for structural calculations, applicable for normal weight concrete, and which is:

$$E_c = 4.73\left(f'_c\right)^{0.5}$$

where $f'_c$ is expressed in MPa. (1)

The ultrasonic pulse velocity was found to be 4.7 km/s. This falls on the upper part of the range for concrete (3.7 to 4.8 km/s for 20 to 60 MPa concrete) while it is well outside that for mortar (3.0 to 4.0 for 20 to 60 MPa mortar).

The slab was tested using a seven-pound sledgehammer, see Figures 4 and 5. It took about 70 blows for a hole to appear through the slab. The concrete at the top was powdering under the blows but there was no indication of tensile cracking. Once the slab thickness was reduced then cracking on the underside of the slab was detected and further blows caused a cone of concrete to shear off from the underside of the slab. A small hole was created, enough for a person to push his hand through, and this was considered to be the failure point for the concrete slab.

### 4.2 Series II – Mix proportioning and volume of fibers

The mix proportions used by others for RPC produced concretes with the required mechanical properties. However, these concretes had a high cement content of 955 kg/m$^3$ and a high silica fume content of 240 kg/m$^3$. Both of these add to the cost of RPC. Partial cement replacement with ground granulated blast furnace slag (ggbs) and pulverised fly ash (pfa) was therefore investigated, see Table 1. It must be noted that the silica fume used for this series of mixtures was in densified form rather than the undensified form and this appears to have affected adversely the 28-day strengths. The strengths obtained
for PC-1 also showed the importance of preventing desiccation of the specimens at the curing temperature of 90°C. The strengths showed an increase from 7 to 14 days (126.5 to 139.5 MPa) but the strength then decreased to 125.1 MPa at 28-days. Specimens were subsequently not only wrapped in wet hessian and polythene sheet but also placed in plastic containers similar to those used for investigating the potential of alkali-silica reaction of aggregates. Post-set heat treatment was found to improve compressive strengths considerably at 7 days. Further work is currently being carried out to investigate the strength increases between 7 and 28 days and thus determine whether the post-set heat treatment needs to be applied for up to 28 days or whether it can be stopped at 7 days.

Partial cement replacement with ggbs, up to 56%, did not have any detrimental effect on the 28-day strength of cubes cured at 20°C. However, demoulding of the cubes for the 36GGBS-1 and 36GGBS-2 mixes was only possible five and three days respectively, after casting. Once the liquid, rather than the powder, form of the polycarboxylate polymer was used then cubes with 36% ggbs could be demoulded the day after they had been cast. Attempts to reduce the water-binder ratio even lower, from 0.21 to 0.18, resulted in a less workable concrete and incomplete compaction may have affected the compressive strengths of 36GGBS-4.

Partial cement replacement by pfa, even as low as 18%, delayed the setting time of the concretes and the cubes could only be demoulded two days after casting. Despite this, strengths as high as 140 MPa were achieved at 28 days when specimens were cured at 90°C.

The proposed use of glass cullet in this research project was to replace the silica sand in RPC, see Glass-1 and Glass-2 in Table 2. Since the mid 1990s, a significant surplus of green glass has started to arise in the UK, due to an imbalance between production and imports. The surplus derives from an imbalance in the relatively large

![Figure 4: Impact testing of RPC](image1)

![Figure 5: Underside of RPC slab after 70 sledgehammer blows.](image2)
quantity of green glass recovered and the smaller quantities of green glass containers produced by the UK glass industry. The generation of a considerable “green glass mountain”, if alternative uses are not identified, could compromise both the economic viability and the sustainability of cullet recovery in the UK. The first batch of ground glass used in Glass-1 and Glass-2 mixes proved not to be fine enough for the pozzolanic reaction to “kick-in” at the curing temperature of 90°C, i.e. the glass may be considered to be an inert filler in this case. The glass cullet was therefore sieved and only particles smaller than 400µm were used for Glass-3 mix. The strengths of cubes cured at 90°C are considerably higher than those of cubes cured at 20°C indicating that the glass has become reactive, i.e. some pozzolanic reaction has taken place. Strengths are also higher than Sand-1 mix which had ordinary sand with particles less than 400µm. The strengths however are not as high as those of 36GGBS-3 indicating that the glass cullet, although reactive, may not be as reactive as silica sand. A second batch of ground glass cullet was obtained from a different supplier and this was a powder rather than an aggregate. Glass-4 mix was an attempt to use this as an aggregate. The total water of the mix, because of the fineness of the glass cullet, had to be doubled in order to get a workable concrete. Glass-5 mix shows that the powder glass can be used as a partial cement replacement.

Addition of fibers to the mix increases not only the flexural strength but also the compressive strength. Flexural strengths of 37.3MPa and 40.3MPa were achieved with 1.5 and 2.5% of fibers by volume respectively. Lower flexural strengths of 24.6MPa and 29.9MPa respectively were achieved with the companion cubes cured at 20°C. All fiber concretes had ductile failures similar to those in Series I and shown in Figure 1.

5 CONCLUSIONS

It has been shown that concretes with compressive strengths as high as 200MPa and flexural strengths as high as 40MPa can be produced in the laboratory. The high cementitious content required for these concretes, approximately 1200kg/m², adds considerably to the cost of their production. Partial cement replacement by ground granulated blast furnace slag has been shown to be beneficial for these concretes. The proposed use of ground green glass cullet to replace the silica sand in a new form of Ultra High Performance Fiber Reinforced Concrete could represent an important advance in dealing with the recycling problems of glass in the UK.

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