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The effect of polypropylene fibres within concrete with regard to fire performance in structures

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Abstract

Purpose – The purpose of this paper is to examine the effect of various polypropylene fibre additions (types and volume) to concrete with regard to explosive spalling when subject to high temperatures similar to those experienced in building or tunnel fires.

Design/methodology/approach – Medium strength concrete was manufactured with varying proportions of polypropylene fibres. Plain control samples were used to determine the original concrete strength and this was used as a benchmark following high temperature heat tests to evaluate the surface condition and final compressive strength. A pilot study was used to determine an appropriate heat source for the test. This was three Bunsen burners, however sufficient heat could not be generated within 150 mm concrete cubes and the concrete was shown to be a significant insulator and fire protection for structural members. The concrete test cubes were tested in a saturated condition which may reflect conditions where concrete is used in an external environment and thus is subject to soaking.

Findings – One hundred and fifty millimetre concrete cubes with and without fibres were placed into a furnace at 1,000°C. Explosive spalling was shown to be reduced with the use of polypropylene fibres but the final compressive strength of concrete was significantly reduced and had little residual structural value after a two hour period of heating.

Research limitations/implications – As the concrete tested was saturated, this condition provided a worst case scenario with regards to the build up of hydrostatic and vapour pressure within the cube. A range of percentage moisture contents would produce a more evenly balanced view of the effects of fibres in concrete. A single grade of concrete was used for the test. As the permeability of concrete influences the rate at which steam can escape from the interior of a saturated concrete cube, testing a range of concrete strengths would show this aspect of material performance with regard to spalling and final residual strength. Further research is recommended with regard to moisture contents, strengths of concrete and a range of temperatures.

Practical implications – This research has significance for the designer, in that buildings subject to terrorist activity may suffer from impact damage and an outbreak of fire following the initial attack.

Originality/value – The use of polypropylene fibres in concrete to provide anti spalling qualities is relatively new and this research adds to the knowledge regarding fibre type and volume with regard to first spall time, total area and number of areas subject to spalling and the final compressive strength of concrete following two hours of raised temperatures.

Keywords Cement and concrete technology, Compressive strength, High temperatures, Fire

Paper type Research paper

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Introduction

The terrorist events in Lower Manhattan on 11 September 2001 highlighted the need for an impact and fire resistant material as part of an overall safe design against impact and heat damage generated from aircraft fuel along with combustible interior finishing. More recently, terrorist attacks in the UK (July 2005) also highlighted the requirement for designers to consider the need to provide increased levels of safety where large numbers of people may be exposed to terrorist attacks in structures designed for their safe occupation (Richardson, 2005).

The performance of the structural frame whether it be concrete or steel determines the degree of safety afforded to the occupants. Concrete can be used as a fire protection or as a structural member with cover to the steel providing fire protection. The performance of this material is critical to the structural integrity of the structure. Explosive spalling occurs during the early part of a fire, usually within the first 30 min or so of a furnace test. It can occur at an early stage just above 150°C. It is characterised by pieces of concrete being violently expelled from the surface. The phenomenon can occur just once or at intervals even from the previously spalled parts. Multiple spalling layers are more likely in High Strength Concrete (HSC) than Ordinary Strength Concrete (OSC) due to its low permeability. Spalling is often restricted to the unreinforced part of the section and usually does not proceed beyond a reinforcing layer.

A reduction in permeability has been found to be detrimental to performance in fire. This is because steam is produced in concrete at high temperatures. Unless there is an escape route for the steam, internal pressures are generated that, in conjunction with other stresses, can exceed the tensile strength of the concrete. In addition, raising of the concrete grade changes the stress-strain characteristics, making the concrete more stiff and brittle. Thermal stresses may therefore be higher and the concrete less accommodating to internal pressures (Clayton and Lennon, 2000, p. 2). The rate that temperature rises inside the concrete when heated, plays a significant role in causing explosive spalling because, if the temperature rate rises quickly then the water content inside of the concrete will want to escape quicker causing a greater amount of steam being produced, therefore leading to the explosive spalling of the concrete. But if the rate of the temperature rises slowly then the steam produced will be produced at a slower rate, thus allowing the concrete time to release the steam.

Materials

19 mm × 22 micron and 40 mm × 0.9 mm polypropylene fibres as used in this research, are classified in BS EN 14889. They fall into two categories: Type 1 (Monofilament < 0.3 mm diameter); and, Type 2 (Macro Synthetic > 0.3 mm diameter). Polypropylene monofilament fibres were used in conjunction with concrete at various volumes. At a rate of 0.9k g/m^3, there are approximately 22 million monofilament fibres/m^3 of concrete of longer length and up to 30 million of shorter length fibres/m^3 of concrete. Type 2 fibres were 40 mm × 0.9 mm diameter and used at a rate of 6.0 kg/m^3. Polypropylene fibres are claimed to reduce explosive spalling in concrete by forming voids which act as pressure relief chambers. When subject to heat (160°C), the polypropylene fibres and monofilament fibres start to melt.

At 360°C, as the heat increases, the fibres start to degrade and ignite, and after this burning process there only remains carbon, which occupies approximately 5 per cent of the void. The voids left by the monofilament polypropylene fibres, allow for the water vapour to escape, thus reducing explosive spalling (Kitchen, 2001). CEM 1 was used with washed natural dredged local aggregates (North east England) to produce the concrete.

Thermal stability test for fibres

The thermal stability of 19 mm Type 1 microfibre was investigated by performing Thermal Gravimetric Analysis and Differential Scanning Calorimetric tests. Testing was conducted on TA Instrument, USA Model SDT 5000/2960 as per ASTM-D-297-72 (1993) provisions. Figure 1 shows the relationship between percentage change in weight and change in °C temperature for 19 mm microfibre. It was observed that from 50°C to 223.55°C there was only 0.8 per cent weight loss in the fibres. At temperature 490°C, almost all the sample was lost due to effects of the temperature (see Figure 1).

Figure 2 shows the relationship between heat flow (W/g) and change in °C temperature for the Type 1 microfibre. One endothermic peak between temperature range 157.25°C to 169.83°C during negative heat flow and one exothermic peak between

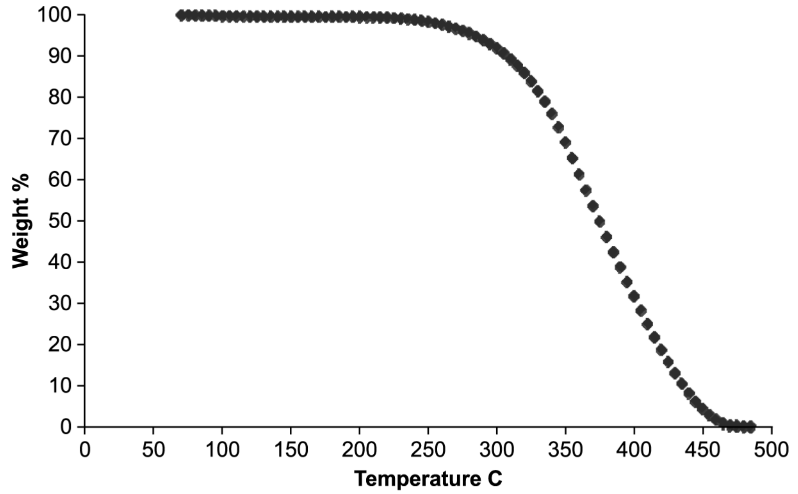


Figure 1.
Thermal gravimetric analysis of fibres

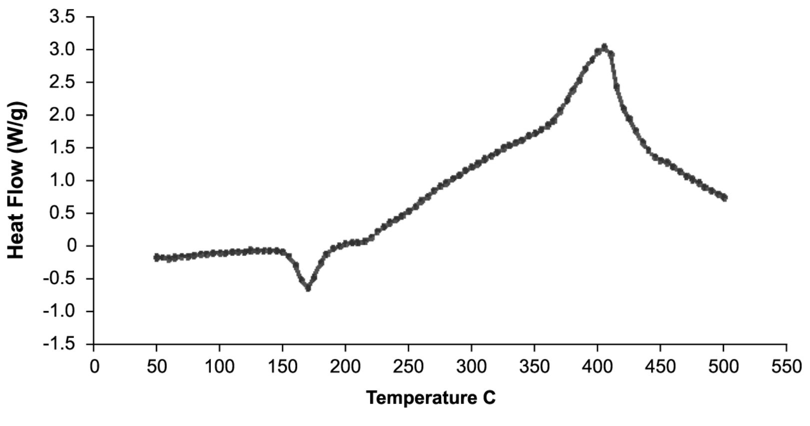


Figure 2.
Differential scanning calorimeter – analysis of fibres

temperature range 360.53°C to 406.68°C during positive heat flow was observed during the experimentation. Melting of polypropylene fibres was observed at 169.83°C.

Justification of sample size

After examination of journal papers reviewed below with regard to acceptable population size, to establish peer reviewed validity of published results, it was noted most concrete researchers described what was produced for testing and subsequent results discovered from the tests, but many omitted to clearly state the population size per sample type.

Researchers who stated their population size clearly were Betterman *et al.* (1995) who used a population size of ten, Qian and Stroeven (2000) used a population size of eight, Mu *et al.* (2002) used a population size of two and Leung (2003) used a population size of five.

The problem with testing concrete cubes is that they are very heavy to move in and out of a furnace and therefore a reduced population sample of five was used to facilitate the practical aspect of testing.

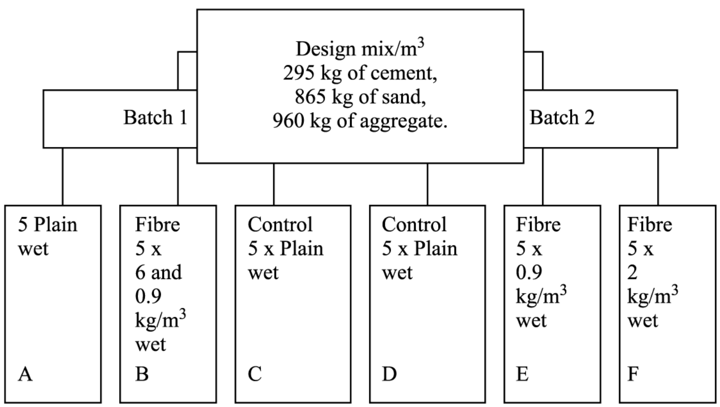
Methodology

A paired comparison test was used comparing unheated concrete with heated concrete for spalled areas and final compressive strength. The furnace temperature was determined by Eagar and Musso (2001) who state, "The maximum flame temperature increase for burning hydrocarbons (jet fuel) in air is, thus, about 1,000°C". This would replicate a fire similar to that following the World Trade Centre attack as well as reflecting the realistic temperature of the fire in a large building or tunnel (Kitchen, 2004, p. 40).

Concrete cubes were manufactured as Figure 3 with a water cement ratio of 0.7.

The main experiment included:

- five water saturated plain concrete cubes;
- five saturated concrete cubes containing 0.9 kg/m^3 of monofilament polypropylene fibres (Type 1);



Note: The cubes were cured for 28 days in a water filled curing tank, then the saturated cubes A, B, E and F were placed in the furnace for the 2 hour firing process

Figure 3.
Concrete design mix for the fire tests

- five saturated concrete cubes containing 2 kg/m^3 of monofilament polypropylene fibres (Type 1);
- five saturated concrete cubes containing 6 and 0.9 kg/m^3 of structural and monofilament polypropylene fibres (Types 2 and 1); and
- a furnace.

Each of the cubes was heated for two hours to reflect the required fire protection to structural elements in the Building Regulations Part B.

The main experiment measured the time to the first spall, the condition of the surface of the cubes, and the compressive strength of the cubes, after being heated in the furnace, these results were compared with the control samples.

The cubes were cured for 28 days in a water filled curing tank, then the saturated cubes A, B, E and F were placed in the furnace for the two-hour firing process.

Ten plain cubes C and D were used for the control sample using compressive strength as a quality indicator, thus allowing comparison between the cubes heated for 2 hours and untested cubes.

Control tests (compressive strength)

Compressive strength test results for the two control batches show the mean compressive strength for control batch C was 34.5 N/mm^2, and the mean compressive strength for control batch D was 29.96 N/mm^2. The batch difference was 13.2 per cent which is acceptable for batch comparison purposes, although it would have been preferred if the difference was single figures.

Pilot study

Test cubes were subject to three bunsen burners applied at full heat for two hours and the internal temperature at thermocouple 3 (130 mm from the flame) did not exceed 49.1°C over a two-hour period, whereas thermocouple 1 (40 mm from the flame) reached a final temperature of 103.1°C over a two-hour time period. (Figures 4 and 5).

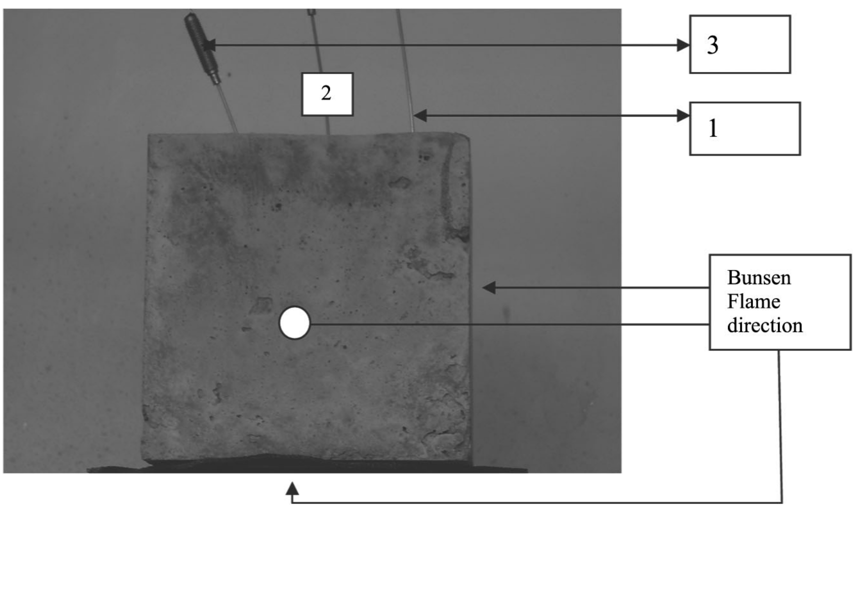


Figure 4.
Control cube for pilot study with thermocouples

Figure 5.
Two-hour bunsen burner pilot test

Ingham and Tarda (2007, p. 27) found that within concrete as subjected to temperatures up to 300°C, "The residual strength of structural quality concrete is not reduced". The test clearly shows the efficacy of the fire protection and insulation qualities of concrete when used as fire protection

Results

Following the two-hour heat test (Figure 6), the cubes were left to cool and examined to evaluate the degree of spalling and the compressive strength.

The final average compressive strength following the furnace test was compared against the control cubes which had an average compressive strength of 32.23 N/mm^2 at 28 days.

The time to initial spalling is shown below:

- plain concrete cubes – 45 minutes to first spall;
- fibre 2 kg/m^3 concrete cubes – 75 minutes to first spall;
- fibre 0.9 kg/m^3 concrete cubes – 105 minutes to first spall; and
- fibre 0.9 + 6 kg/m^3 concrete cubes – 105 minutes to first spall.

The time to the first spall is significant in that, if the fire is of a short duration, concrete with polypropylene fibre additions will receive greater protection against spalling when compared to plain concrete.

Figure 7 shows a representative example of a spalled concrete cube following a two hour fire test showing the surface carrying major cracks and a pop-out explosion spalling – with the perimeter of the exposed aggregate showing.

The final condition of the spalled cubes is show in Table I, with regard to the number of spalled areas and mass lost, based on the dry weight of the test samples.

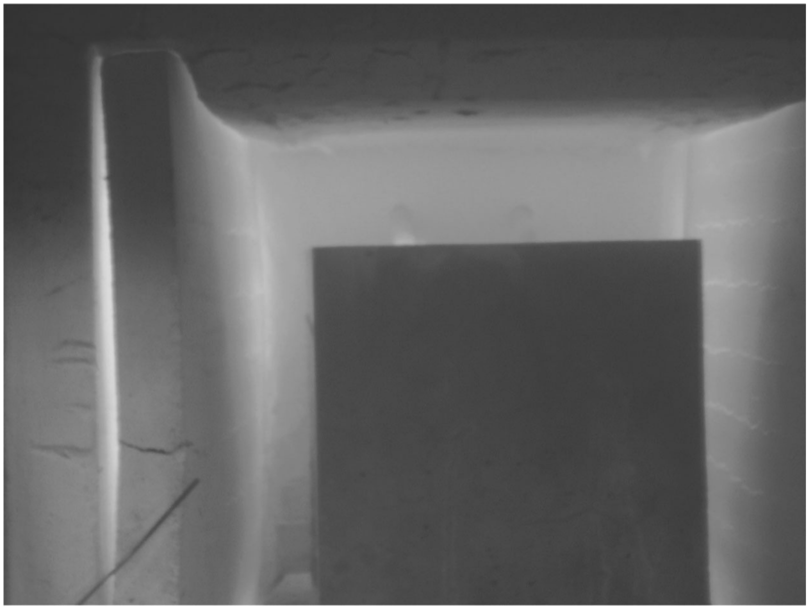


Figure 6.
Concrete cube in 1,000°C furnace

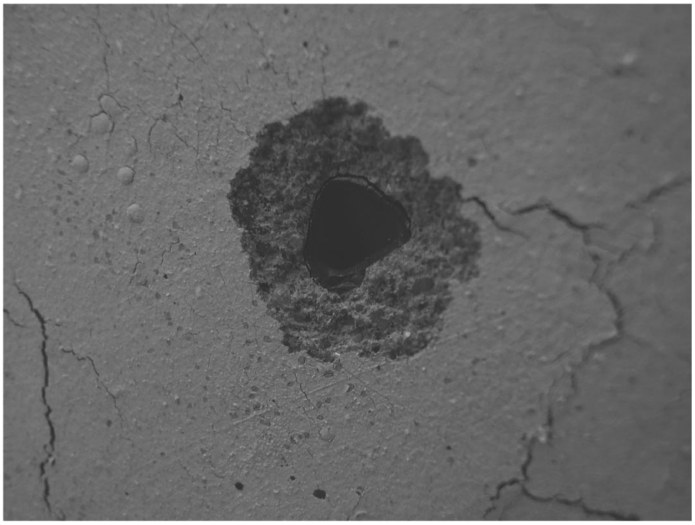


Figure 7.
Explosive spalling on face of concrete cube

Table I.
Average quantity of spalled areas per cube and mass lost

Cube type	Mean number of spalled areas per cube	Mean % mass lost
Plain	10	0.58
Fibre 0.9 kg/m^3	8	0.49
Fibre 2 kg/m^3	2	0.099
Fibre 0.9 + 6 kg/m^3	2	0.11

From Table I it was observed that the plain concrete cube samples spalled more times than any other concrete cube type. Visual inspection of the concrete surface following a fire was used to determine the degree of damage.

Following the heat test, surface colouration of the concrete was observed to be whitish grey in colour and when compared to TR 33 (Concrete Society, 1990) this indicates damage to class 3 necessitating a principal repair requirement.

The final compressive strength of all of the heat tested cubes produced a mean value of 16.44 N/mm^2 with no discernible difference between concrete manufactured with monofilament polypropylene fibres and without fibres. The mean differences between the control samples and the test cubes following a two-hour firing was a 49 per cent reduction in compressive strength.

This compressive strength reduction was expected as according to Ingham and Tarda (2007, p. 30) "concrete heated in excess of 600°C is of no use structurally". What this test did establish; was the strength reduction expected following a lengthy fire. This strength reduction would determine the degree of collapse to be expected or the service limit state which would be exceeded, following a fire. The post heat test compressive strength information will assist the designer in producing a building that is safe with regard to means of escape.

The role of polypropylene fibres in protecting concrete against the effects of high temperature

Spalling in concrete is caused by high internal pressure, due to exposure to higher temperatures. The reasons for this phenomenon under cyclic temperature exposure, are vapour pressure build-up within the hydrated cement paste and thermal expansion of the aggregates. Micro-cracking observed in concrete on the surface is generally caused by thermal expansion between aggregate grains and the surrounding cement paste. A further reduction in strength can be attributed to the cooling of concrete in air. This is due to formation of tensile stresses during the contraction of hardened cement paste upon cooling, which when superimposed onto the existing tensile stresses formed during heating, cause an increase in the amount and rate of crack formation. With regard to the use of fibres in concrete; heating causes de-bonding of the fibre matrix interface due to differential co-efficient of expansion even before applying any external load.

Pore structure seems to have a significant influence on hydrothermal behaviour of concrete. The addition of polypropylene fibres affects the release of moisture from the concrete and reduces vapour pressure by providing additional pore space for vapour accumulation. Polypropylene fibres have when heated, produced partial melting of the fibres. Melting of polypropylene fibre is considered as an extremely positive development for concrete. It is very easy for the cement matrix to absorb the melted polypropylene, and by this way a new pathway is generally created for water, vapour, gas etc. In this way, polypropylene fibres contribute to the creation of a network which is essentially far more permeable than the cement matrix. This allows the outward migration of gas and ultimately results in reduced pore pressure. Melting of polypropylene fibres also enables the vapourization and expelling of water at a reduced temperature. Thus a higher pressure drop would be expected in concrete with fibre additions mixes compared to control concrete. This suggests the role played by polypropylene fibres will create a network of more permeable concrete. The direct contribution of polypropylene fibres is evident in reducing the stress fields due to pore pressure. During thermal exposures, polypropylene fibres also have an influence on the microstructure of concrete as well as on the hydrous field in concrete. In concrete, a hydrous field is coupled with the thermal field. This results in a decrease of temperature differential through polypropylene fibre concrete specimens, during exposure to temperature, whereas in control/plain concrete specimens, water dehydration leads to a high thermal gradient. This can also be suggested as the reason for the superior performance of concrete with fibres, compared to plain concrete.

It was observed that monofilament polypropylene fibres as used, were able to reduce the spalling of concrete significantly, when compared to plain concrete. Therefore these fibres could be recommended to be used in several applications of civil engineering where the concrete is likely to be subjected to higher temperature during the entire service life of the structure i.e. fire protection, refractory, turbojet runways, industrial furnaces.

Conclusion

It was concluded that monofilament polypropylene fibres reduce explosive spalling when used as a concrete additive. Increased fibre content did affect the anti spalling performance of the concrete when compared to plain concrete. More tests are required to establish precise data with regard to fibre content effectiveness to prevent spalling, particularly with different strength concrete and different moisture contents. If concrete is subjected to prolonged elevated temperatures it requires careful evaluation to determine the final residual compressive strength to prevent ultimate limit state failure.

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