Polypropylene Fibres Within Concrete with Regard to Heat Induced Spalling and Reduction in Compressive Strength

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ABSTRACT

The paper examines the effect of various polypropylene fibre additions (Types 1 and 2 and different fibre volumes) to concrete with regard to explosive spalling when subject to high temperatures similar to that experienced in building or tunnel fires.

The pilot study used to determine an appropriate heat source for the test showed concrete to be a significant insulator and fire protection for structural members.

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 2 hour period of heating.

Keywords: Monofilament polypropylene fibres, spalling, compressive strength

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1.0 INTRODUCTION

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: 2).

The rate that temperature rises inside of 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.

1.1. Originality

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 2 hours of raised temperatures. 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. Polypropylene fibres may provide improved fire protection under these circumstances.

2.0 METHODOLOGY 2.1

Justification of sample size

After examination of journal papers as listed 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 10, Qian and Stroven (2000) used a population size of 8, Mu et al (2001) used a population size of 2 and Leung (2003) used a population size of 5.

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 to facilitate the practical aspect of testing.

- The main experiment included:
- 5 water saturated plain 150 mm concrete cubes
- 5 saturated 150 mm concrete cubes containing 0.9 kg/m^3 of monofilament polypropylene fibres (Type 1)
- 5 saturated 150 mm concrete cubes containing 2 kg/m^3 of monofilament polypropylene fibres (Type 1)
- 5 saturated 150 mm concrete cubes containing 6 and 0.9 kg/m^3 of structural and monofilament polypropylene fibres (Type 2 and Type 1)
- An electric furnace

Each of the cubes was heated for 2 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 in the furnace were heated to 1000°C to reflect the realistic temperature of the fire in a large building or tunnel (Kitchen 2004:40). 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 2004:40). The design mix for the experiment is shown below (Figure 1)

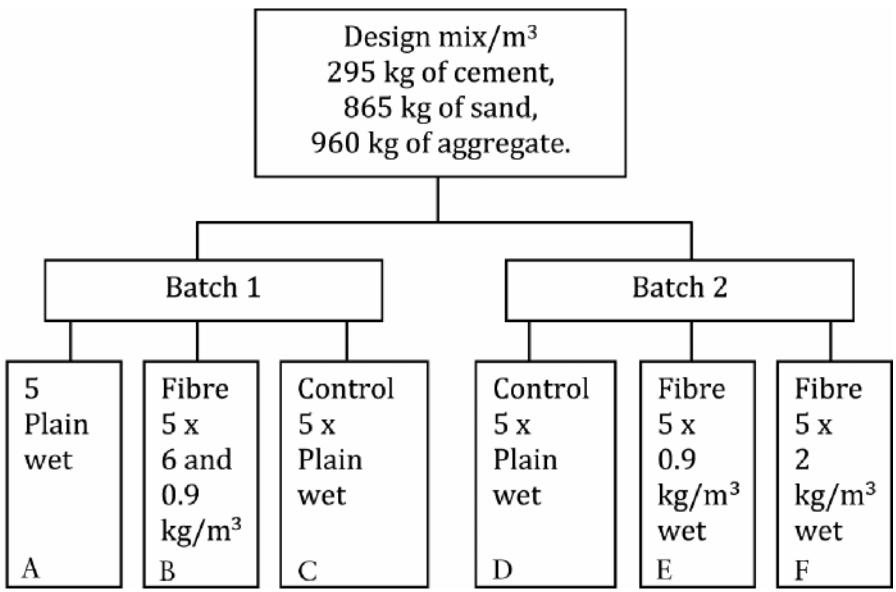

Fig 1.0, Concrete design mix for the heat tests

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. 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.

2.2 Materials

19mm x 22 micron and 40 mm x 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 0.9kg/m^3, there are 22 million monofilament fibres/m^3 of concrete or up to 30 million for shorter length fibres/m^3 of concrete.

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 3 60°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% of the void.

The voids left by the monofilament polypropylene fibres, allow for the water vapour to escape, thus reducing explosive spalling. (Kitchen 2001)

2.3 Control tests (Compressive strength)

Compressive strength test results for the two control batches show the mean compressive strength for control batch 1 was 34.5 N/mm², and the mean compressive strength for control batch 2 was 29.96 N/mm². The batch difference was 13.2% which is acceptable for batch comparison purposes, although it would have been preferred if the difference was single figures.

2.4 Pilot study

Test cubes were subject to a bunsen burner 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 2 hour period, where as, thermocouple 1 (40 mm from the flame) reached a final temperature of 103.1°C over a 2 hour time period. (Figure 2).

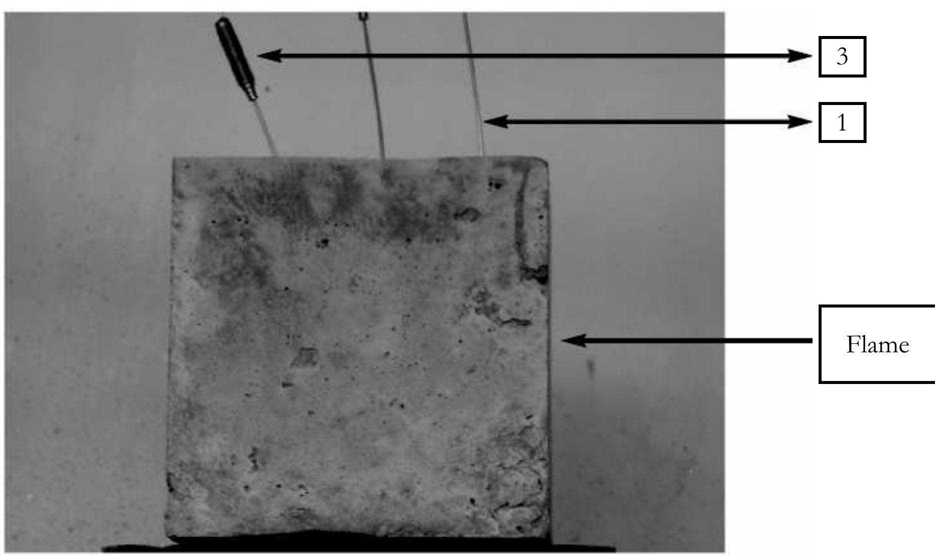

Fig 2.0, Control cube for pilot study with thermocouples

Ingham and Tarda (2007:27) found that within concrete as subjected to temperatures up to 3 00°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.

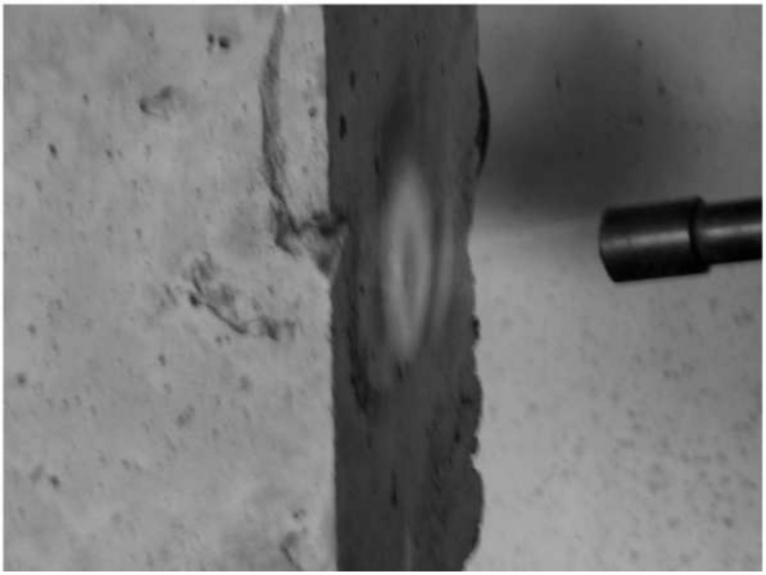

Fig3.0, 2 hour bunsen burner pilot test

3.0 RESULTS

Following the 2 hour heat test (Figure 4), the cubes were left to cool and an examined to evaluate the degree of spalling and the compressive strength.

Figure 4 – Concrete cube in 1000°C furnace

The compressive strength was compared against the control cubes.
The time to initial spalling is shown in Table 1:

- plain concrete cubes - 45 minutes to spall
- fibre 2kg/m³ concrete cubes - 75 minutes to spall
- fibre 0.9kg/m³ concrete cubes -105 minutes to spall
- fibre 0.9 + 6kg/m³ concrete cubes - 105 minutes spall.

Figure 5 shows a representative example of a spalled concrete cube following a 2 hour fire test.

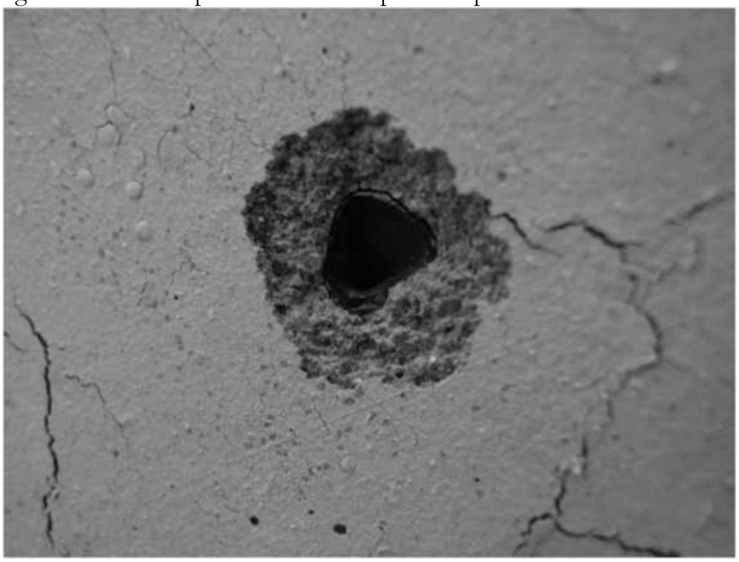

Fig5.0, Explosive spalling on face of concrete cube.

The final condition of the spalled cubes is show in Table 1.

Cube	Mean number of spalled areas
Plain	10
Fibre 2kg/m³	2
Fibre 0.9kg/m³	8
Fibre 0.9 + 6kg/m³	2

Table 1 Quantity of spalled areas per cube

From Table 1 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 cubes produced a mean value of 16.44 N/mm² with no discernable difference between concrete manufactured with monofilament polypropylene fibres and without fibres. The mean differences between the control samples and the cubes following a 2 hour firing was a 49% reduction in compressive strength.

This compressive strength reduction was expected as according to Ingham and Tarda (2007:3 0) "concrete heated in excess of 60 0°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.

4.0 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. 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.

5.0 RESEARCH LIMITATIONS

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.

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