Concrete porosity with polypropylene fibres and silica fume

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Abstract

Purpose -This research examines the effects of Type 1 and Type 2 synthetic polypropylene fibres in concrete, with and without silica fume, regarding porosity. The raison d'être for the research is to examine the porosity of fibre concrete where the concrete may be subject to a hydrostatic pressure from water. The use of silica fume defines the positive benefits that can be achieved by utilising a waste/by product in a concrete mix.

Methodology – The standard for determining the penetration depth of water under pressure (BS 12390: part 8 2009) in concrete was used with two types of synthetic fibre (Type 1 and Type 2) and plain concrete, with and without silica fume were subject to a water pressure test over 72 hours to determine the depth of water penetration.

Findings - The findings showed that synthetic fibres when added to a concrete mix increase the porosity of the concrete when compared to plain concrete, however when additional silica fume is used at a dry rate of 10% to the dry mass cement content or 20% slurry content, the porosity of the concrete is significantly reduced.

Originality – Designers and contractors use fibre reinforced concrete to create water retaining structures. Low permeability equates to more consistent and better stored water quality. This research demonstrates the effectiveness of silica fume, which improves the performance of the concrete with regard to porosity and mitigates the effects of the synthetic fibre inclusion. Low absorption in concrete equates to low life cycle costs and good sustainability credentials through the use of a by product.

Key words: porosity, synthetic fibres, silica fume, concrete, durability

1.0 Introduction

In the North East of England, reinforced concrete service reservoirs have been constructed using polypropylene fibre technology (Seymour 2011). The purpose of the synthetic fibre inclusion is to reduce drying shrinkage cracking and to manufacture a crack free structure to hold drinking water. A clear advantage of synthetic fibre technology in a drinking water environment is that they do not corrode and cause contamination of the water supply. Previous research has shown that Type 1 monofilament polypropylene fibres have a small but positive effect in reducing absorption in concrete (Richardson 2004), however when water is stored in large quantities and at significant hydraulic depths, water movement/transmission in concrete under pressure is by a different means to that of absorption.

Hanzic, Kosec and Anzel (2010 :1), suggest that, 'Moisture is one of the major factors that contribute to deterioration of concrete. Transport of liquids in porous media such as concrete takes place in open pores mainly due to diffusion, suction and capillary absorption. The driving forces of the diffusion and suction processes are concentration and the pressure gradient, respectively, whereas capillary absorption is driven by surface tension. The water existing in pores bigger than 50 nm behaves as free water and it plays an important role in the durability or the lack of durability of concrete (Garboczi & Bentz 1995).

When concrete is drying it shrinks, this 'shrinkage' causes macro and micro cracking. The cracking occurs due to the low tensile strength of concrete that cannot withstand the stresses of the shrinkage occurring throughout the curing period. This micro-cracking is prone to progressing into macro cracking. The macro-cracking propagates and exposes the concrete to attack by aggressive media.

In recent years with the introduction of structural fibres, researchers have been able to change the characteristics of concrete with regard to this cracking; this has in turn allowed the to facilitation of lean design. The fibres help to control cracking much like reinforcing steel only in 3D. The concrete binds to the fibres and the tensile stress of the shrinkage with the concrete during the curing period is redistributed and this largely eliminates cracking.

An aspect of these fibres being mixed into the concrete that has perhaps been overlooked is the potential for them to increase concrete porosity. Whilst the introduction of these fibres has proved beneficial in controlling surface cracking, there is limited data available that investigates the effect of these fibre additions on the porosity of concrete and this paper addresses this shortfall.

Silica fume is a by product of the steel making process and when included in the concrete mix and used at the correct dosage, it significantly reduces porosity due to its pore blocking effect (Domone and Illston 2010:107). Due to its fineness, it enters the pore matrix of the concrete and 'closes' any potential paths along which penetration of deleterious substances can occur. Silica fume is said to have a low bulk density meaning that it can be highly concentrated and yet not use up a great amount of space. Asrara *et al* (1999:1) comments that, 'Silica fume is a mineral that improves the corrosion protection and strength of concrete by reducing the permeability of the concrete.' Due to silica fume's fineness (sizes ranging from 0.03-0.3µm Domone and Illston (2010:107)) and large surface area it enters voids in the concrete that the cement particles cannot access due to the average size of 10 µm. The introduction of the silica fume into the concrete matrix reduces or eliminates (depending on the percentage added) the passage that liquids, gases and ions would otherwise have been transmitted. Meddah and Arezki (2009) agree; commenting that the use of silica fume in the mixture of concrete 'increases the density of concrete and refines the pore structure. Whilst there appears to be little negative effects of the use of silica fume in the concrete mix design there is a pragmatic problem. This problem is the high economic cost of silica fume. It is an expensive material to harvest and is therefore considered to be an uneconomical use of funding to purchase it unless the service environment demands its use.

Type 1 polypropylene fibres can be effective in reducing the amount of bleed in concrete. Bleeding occurs as concrete is setting, there is an upward migration of water to the surface. Too much bleeding can weaken up to 2% of the depth of the concrete. This can easily lead to cracks and therefore durability problems by reducing the cover to reinforcement steel within the concrete (Domone and Illston 2010:127). With the inclusion of silica fume in concrete bleeding is likely to be reduced to zero or minimal amounts that are negligible. This is due to the higher density of the concrete and refined pore structure leaving little 'free water' (Meddah and Arezki 2009). The combined effects of Type 1 polypropylene fibres and silica fume may provide a homogeneous concrete mix with enhanced durability qualities if the mix is correctly proportioned.

2.0 Materials

The materials were stored in a laboratory prior to being used and were sourced locally in the North East of England. The addition of fibres within the concrete mix is for the purpose of bridging the cracks and micro cracks that can occur through interactions with the environment. The use of fibres in concrete lowers the density of the material when compared to plain concrete; by entraining air into the concrete (Richardson 2006), this is not a quality required if the concrete is to have low permeability. The materials used are outlined in sections 2.1 to 2.3 with the exception of the mixing water which was compliant to BS EN 1008:2002.

2.1 Fibre types

Polypropylene is a large molecule built up by a repetition of a small simple chemical unit until a polymer chain is formed. It is a relatively modern product and was not manufactured until 1957 (Billmeyer 1984:11) following innovative work by Staudinger (1920) and Flory (1937) both receiving the Nobel prize for their work. The length of this chain is known as the degree of polymerisation (DP) and it is determined by number of repeat units in the chain. The molecular weight can be determined by multiplying the DP by the molecular weight of the chain. Polypropylene is a hydrocarbon containing only chemical elements; therefore it is often referred to as a hydrocarbon polymer. Hydrocarbon polymers consist of simple chemical structures and are built entirely from carbon and hydrogen atoms.

The Type 1 fibres as used were 20mm in length and 20µm in diameter and the Type 2 fibres were 40mm in length and 1mm in diameter with surface undulations (crimped) and both fibres complied with BS EN 14889. The dosage rates were 0.9 kg/m^3 for Type 1 and 6 kg/m^3 for Type 2 fibres which are within the manufacturers recommended dosage range.

2.2 Cement

CEM 1 was used in this study and is made from a mixture of limestone ($CaCO_3$) and clay, shale ($Al_2O_3.2SiO_2$) or other alumino-silicate. These are finely ground and calcined at a temperature of about 1500^{o}C to form a partially fused mass, or clinker. CO_2 is liberated from the limestone. The clinker is composed of calcium silicates (e.g. $3CaO.SiO_2$ and $2CaO.SiO_2$), and calcium aluminates (e.g. $3CaO.Al_2O_3$ and $4CaO.Al_2O_3.Fe_2O_3$). The clinker is finely ground, and a small quantity of gypsum ($CaSO_4.3H_2O$) added to retard the setting rate, to produce CEM1 which is also known as Portland Cement.

2.2.1 Silica fume

Silica fume is approximately 1/100th the size of a grain of cement [sizes ranging from 0.03-0.3µm (Domone and Illston 2010:107)]. Due to its fineness it enters the pore matrix of the concrete and 'closes' any potential paths along which penetration of deleterious substances can occur. As the particles are amorphous silica (+85%SiO^2) with an extremely high surface area, they react chemically with the calcium hydroxide from the cement to form calcium silicate hydrates or CSH. CSH is the hydration product found in hardened cement paste. Increased CSH leads to higher strength and a pore-blocking effect, which reduces the permeability of concrete, thus enhancing qualities of durability.

The manufacturers recommended dosage is 15 – 25% by weight of cement and the slurry was added to the mixing water prior to adding to the mix. The silica fume used in this research was an aqueous suspension with amorphous silicates, used at a rate of 20% by mass of the cement content.

2.3 Aggregates

The UK is fortunate in having ample supplies of sound natural aggregates (Eglington 1987:21), which include sandstone, limestone, granite, basalt, dolerite, flint gravel and silica sand. The individual testing of the transport properties, hardness and chemical composition of aggregates was not considered necessary.

A sound limestone and some sandstones have transport properties of 1.72 x 10^{-4} m/s as a permeability coefficient (Hobbs 1999:1096). This equates to a w/c of 0.44, which is below the point where concrete is considered to be permeable and therefore durability is not a problem.

Aggregate size is a factor, with regard to durability, with smaller particles causing less disruption, because the average distance to an escape boundary on the aggregate surface is less and smaller aggregates will cause less internal stress within the concrete during the plastic phase before initial setting takes place (Stark & Klieger 1973).

For the sake of this study, the maximum sieve size used was 20 mm for natural coarse marine sandstone aggregates as used in the concrete design mix, which were from a single UK supplier. The fine aggregates were also natural sandstone with 40% passing a 600 μm sieve. Reducing the aggregate size reduces the risk of defects in manufacture due to plastic settlement. Therefore the maximum aggregate size was limited to 20 mm.

3.0 Methodology

This research has been undertaken using a porisometer, which is to test the porosity of concrete by comparing water penetration depths of plain, Type 1 and Type 2 fibre concrete against Type 1 and Type 2 fibre concrete with a 20% silica fume slurry addition as a percentage of the dry cement content and measure the relative performance of each material.

The batching was carried out as Figure 1 (Test Programme) and there were nine plain concrete samples made. Six of these were for porosity testing while the remaining three were tested to determine compressive strength to BS 1881 Part 116: (1983). Three 150 mm fibre cubes were batched for each type of concrete as shown.

The compressive strength test was to determine the relative batch consistency and whether or not the concrete in its hardened form had cured to a consistent degree to allow the test to be relevant.

Test programme

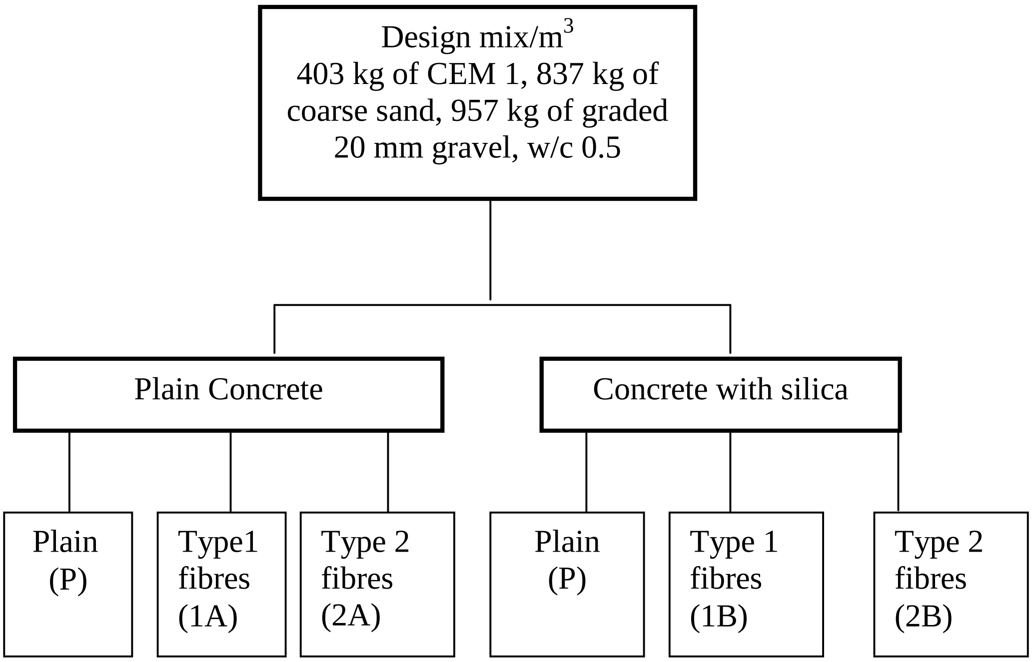

Figure 1 – Batching programme

The test method for the concrete samples was carried out accordance with British Standard 12390 for porosity. The concrete samples had a minimum dimension of 150mm across the face to be tested, and diameter of 75mm for the pressure testing area. A porisometer as shown in Figure 2 was used to determine the porosity of the different concrete types. The procedure was to prepare the surface in contact with the seal and place the cubes under 5kPa of water pressure for 72 ± 2 hrs. After 72 hours under pressure the cubes were split in order to measure the depth of water penetration within the concrete. The splitting of the cubes was carried out using an Elle compression apparatus with a 150mm x 25mm x 10mm strip of medium density fireboard (MDF) placed directly in the centre of the platen, which created the necessary shear force to split the cube.

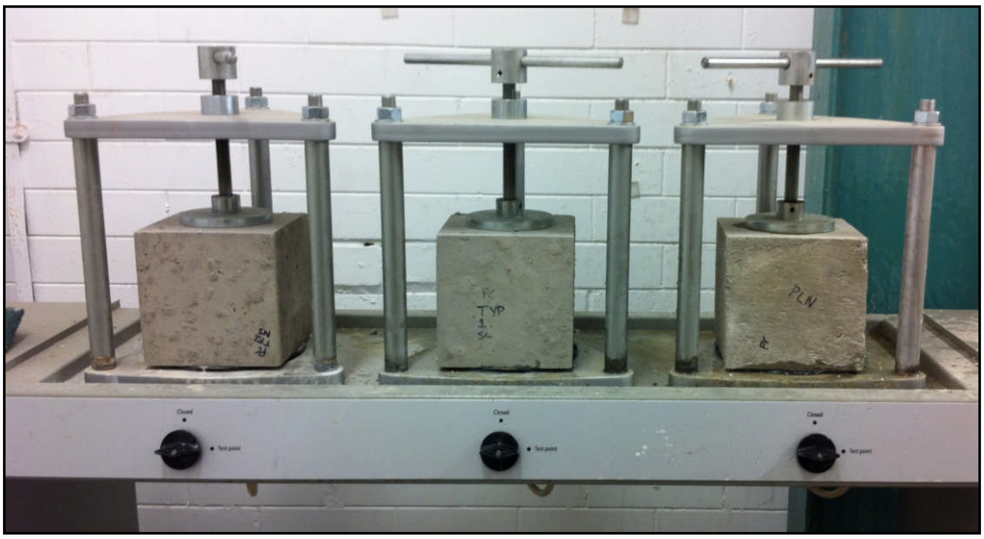

Figure 2 - Porisometer with three concrete samples

As concrete cures continually, the test program had to be carried out to provide sensible average results to ensure accurate analysis. The BS test procedure asks for a 28 day test and this is not possible on a large range of samples due to the fact there were only three pressure plates available at any one time, therefore the testing was started at 21 days and completed at 35 days. The test procedure is shown in Figure 3 and this provided an average of a 28 day curing to measure water penetration depth in relation to porosity over the range of samples tested with the individual tests starting on Monday and Friday. The cube classification as shown in Figure 3 is as follows:

P Plain concrete sample
1A Concrete sample containing Type 1 fibres
1B Concrete sample containing Type 1 fibres and SF
2A Concrete sample containing Type 2 fibres
2B Concrete sample containing Type 2 fibres and SF.

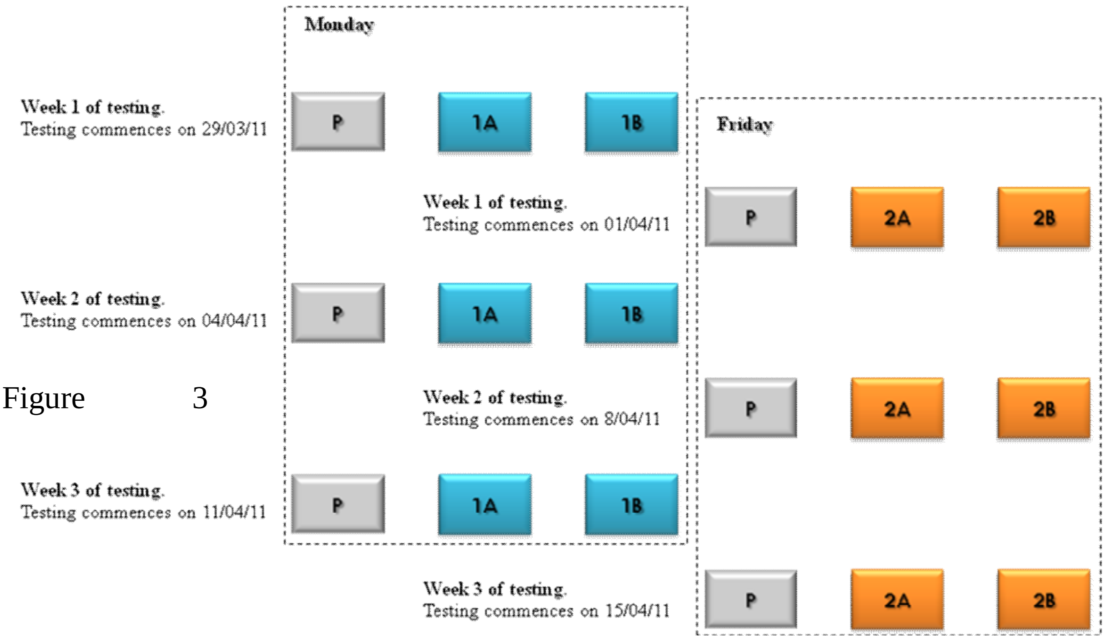

Figure 3 Testing schedule for the porisometer.

4.0 Results

The mean compressive cube strength of the plain samples (n=3) was 37.76 N/mm^2 which is within acceptable tolerances for the C35 mix as set out in BS 5328. Following 72 hours of water pressure, the cubes were split and the maximum depth of water penetration was recorded. Tables 1 & 2 show the depth of water penetration into the concrete cubes. The results represent the measurements taken of the depth of penetration at the epicentre of the water pressure which was a conical triangle of water.

Age of sample in days	Water penetration (mm)		
	Plain	Type 1 fibres with SF	Type 1 fibres without SF
21	34.59	27.89	39.50
28	22.98	12.41	33.47
35	32.37	27.91	32.02

Table 1 - Water penetration – Type 1 fibres

Age of sample in days	Water penetration (mm)		
	Plain	Type 2 fibres with SF	Type 2 fibres without SF
25	26.80	25.14	36.12
32	26.82	24.30	38.22
39	30.59	18.91	25.42

Table 2 - Water penetration - Type 2 fibres.

The information in the data Tables 1 and 2 appears to show an association between heightened concrete porosity and the introduction of the polypropylene fibres (Type 1 and Type 2). It also suggests that the inclusion of the silica fume product counteracts the negative effect of the fibres on the porosity of the concrete.

These initial impressions given by the data need to be substantiated through further analysis. A T-test was used to determine whether or not the different design specifications, i.e. the fibre and SF inclusion in the samples tested, did have a significant effect on the porosity of the concrete.

4.1.1 T-test results

To determine the significance of the results, a T test was carried out across the sample range and the results are shown in Figure 4. The porosity of plain concrete (n=6) was to a mean penetration of 29.03mm. In comparison, the addition of both Type 1 fibres (n=3) and Type 2 fibres (n=3) was shown to increase the porosity of the concrete sample to a depth of 32.79mm ($p \leq 0.01$) and 33.25mm ($p \leq 0.01$), respectively. However, the addition of silica fume to both Type 1 and 2 fibres significantly decreased porosity, in comparison with plain concrete, to a depth of 22.74mm ($p \leq 0.01$) and 22.78mm ($p \leq 0.01$), respectively.

Samples containing Type 1 fibres (n=3) showed a higher degree of porosity ($p \leq 0.05$) compared to samples that were cured containing the combination of Type 1 fibres and silica fume (n=3); the mean water penetration for each set of samples was 33.79mm and 22.74mm, respectively. Similarly, the same effect was observed with Type 2 fibres ($p \leq 0.05$).

When comparing changes in the levels of porosity between samples containing Type 2 fibres (n=3) and samples that contained Type 1 fibres (n=3), it was shown that the change was not significant (NS). This was also true when comparing in like manner the Type 1 fibre & silica fume samples (n=3) against the Type 2 fibre & silica fume samples (n=3).

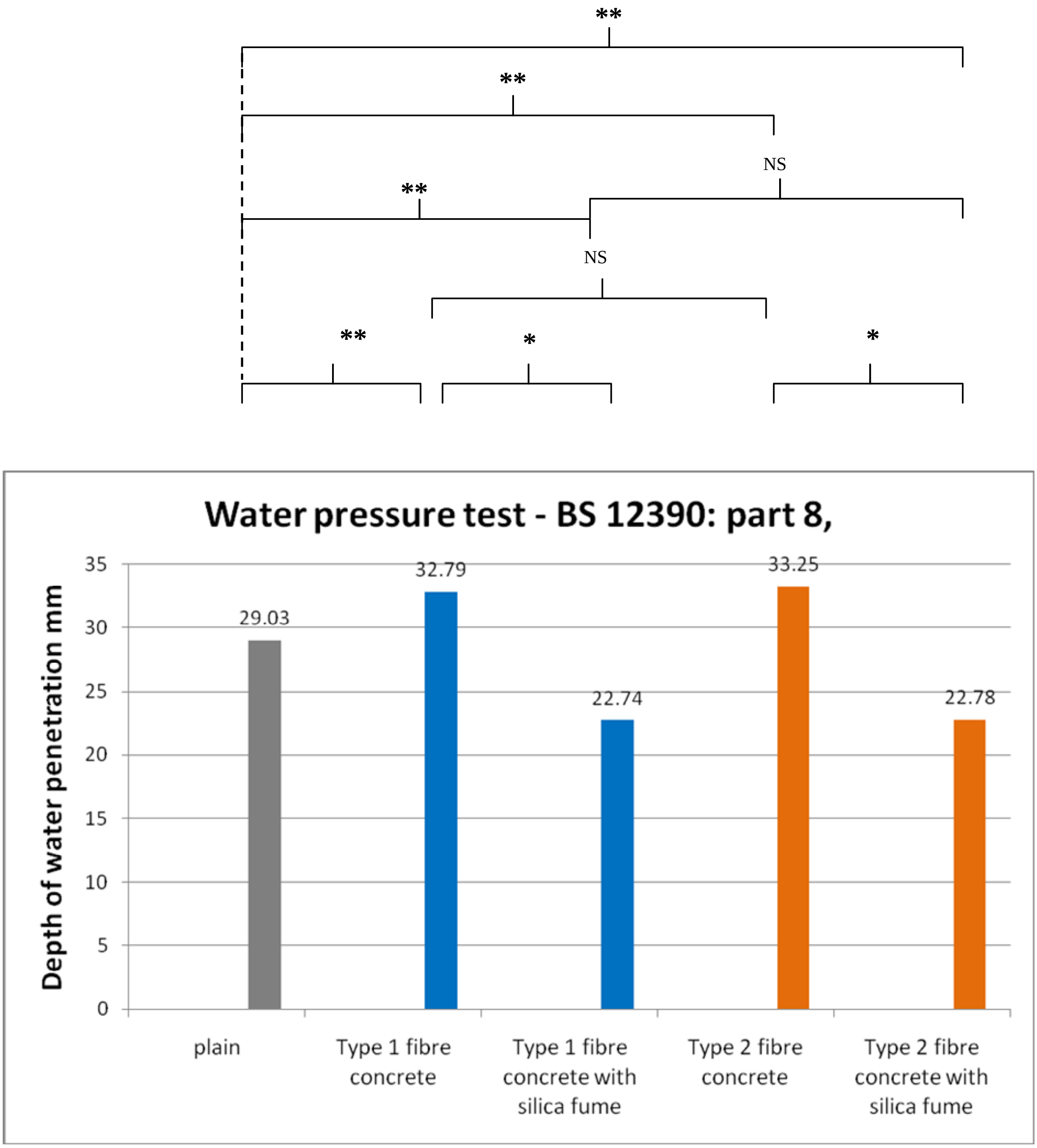

Figure 4 – Mean water penetration values and T-test

Figure 4 Legend

**	Relates to a statistical significance $p \leq 0.01$
*	Relates to a statistical significance $p \leq 0.05$
NS	Relates to data that is statistically insignificant

5.0 Conclusion

The results show that the addition of polypropylene fibres to concrete increases the porosity, and can therefore potentially compromise its resistance to the passage of moisture/liquids/gases. This in turn may reduce the durability of the concrete. When silica fume, is used, a significant lower the porosity of concrete is observed.

This study shows that the increased porosity of concrete due to the addition of polypropylene fibres is effectively countered by the inclusion of silica fume slurry at 20% of the dry cement content. Its introduction significantly reduced the porosity below that of plain concrete alone. These findings suggest that it may be important to consider including silica fume in tandem with Type 1 and/or Type 2 polypropylene fibres to obtain the synergistic effect of all the materials, if low porosity is a design requirement. This will retain the benefits obtained from the use of both Type 1 and Type 2 fibre technology whilst maintaining a low porosity as low porosity equates to high durability and lower life cycle costs.

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