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INFLUENCE OF POLYPROPYLENE FIBERS ON THERMAL-INDUCED PERMEABILITY CHANGES IN CONCRETE

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Abstract: During a fire, concrete structures experience rapid heating leading to thermal instability (spalling), compromising load-bearing capacity by reducing the concrete's cross-section or exposing steel reinforcement to flames. Polypropylene fibers are recognized for their effectiveness in mitigating instability risks. The study aims to enhance understanding of fiber's behaviour during heating to optimize their dosage and limit adverse effects on fresh concrete. Four concretes have been studied with calcareous gravels and mortar aggregates, with and without polypropylene fibers. Two samples of each concrete type were tested: C1-0 (calcareous aggregate), C1-18/32(0.5) (calcareous aggregate with fibers), C1MA (mortar aggregate), and C1MA-18/32(0.5) (mortar aggregate with fibers). The use of mortar aggregates allows us to investigate the influence of thermal mismatch and to better understand the interaction between several phenomena: cracking due to thermal mismatch and porosity and cracking due to fiber melting. Controlled heating from 80°C to 450°C at a rate of 2°/min was conducted, followed by a 3-hour stabilization before radial permeability testing. Results indicate a temperature-dependent increase in intrinsic permeability across all concrete types, with mortar aggregates showing lower permeability values. Mortar aggregate induces minimal thermal mismatch compared to calcareous aggregate, owing to its similar expansion and shrinkage characteristics to cement paste. This reduced thermal mismatch results in fewer cracks when exposed to elevated temperatures, further contributing to the lower permeability of concretes containing mortar aggregate. In contrast, fiber-reinforced concretes exhibited higher permeability, primarily due to the melting and expansion of polypropylene fibers around 170°C. Overall, these findings suggest that the mechanism that increases permeability and reduces spalling is primarily linked to the addition of fibers. While polypropylene fibers are effective in enhancing concrete's permeability and minimizing thermal instability, the thermal expansion of aggregates also has a high influence in this risk. Further research would explore the effects of mechanical loading on the intrinsic permeability of these concrete types and investigate polypropylene fibers with varying geometries and dosages to compare results with the current findings.

1 INTRODUCTION

Concrete serves as a pivotal material in modern construction, valued for its mechanical strength, versatility and durability. However, its performance can deteriorate under elevated temperatures due to significant microstructural changes, including cracking, inducing permeability variations. These issues are particularly critical in fire scenarios, where structural integrity and safety are of paramount concern. Addressing these challenges has been the focus of extensive research on innovative materials and design strategies [1-5]. For this study, concrete samples were prepared using both calcareous gravel and mortar aggregates (crushed mortar with the same mix as concrete but without gravel), with and without polypropylene (PP) fibers. The thermal behaviour of calcareous aggregates and hardened cement paste differs significantly when exposed to elevated temperatures as seen in Fig. 1. Cement paste expands between room temperature and 150°C due to the movement of water molecules and reduced capillary forces. Beyond 150°C, it shrinks as the C-S-H gel and other hydrates dehydrate. In contrast, aggregates tend to expand under these conditions. This thermal incompatibility, or thermal mismatch, induces internal stresses, promoting crack propagation and increasing permeability [6-10]. By using mortar aggregates in this research, the effects of reduced thermal mismatch are investigated, allowing a detailed analysis of interactions between thermal stress-induced cracking and porosity resulting from fiber melting and perhaps to their radial thermal expansion just before melting consecutive to phase change. Research from other authors attributes that swelling of fibers after melting induces microcracks in the concrete.

Polypropylene fibers play a key role in enhancing concrete's fire resistance. At approximately 170°C, these fibers melt, forming microchannels that enable vapor escape, reducing internal pressure and mitigating spalling risks [11-14]. Research conducted using NMR shows that increased permeability due to the creation of these channels contributes to thermal stability by alleviating pressure build-up and allowing faster migration of water leading to a quicker reduction in water content in the areas most exposed to high temperatures. Mortar aggregates, on the other hand, exhibit thermal expansion properties closer to cement paste, effectively minimizing thermal mismatch and its associated cracking. These characteristics lead to reduced permeability and greater thermal resilience compared to calcareous aggregates [15-16].

This study investigates the combined influence of polypropylene fibers and aggregate types (calcareous and mortar) on the permeability of concrete under high-temperature exposure. Samples are heated from 80°C to 450°C at a slow rate and cooled down gently before radial permeability testing. To avoid creating high thermo-mechanical stresses, the heating and cooling rate of the furnace was programmed to 2 °C/min with a stabilization duration of 3 hours to ensure uniformity of the temperature across the sample.

The results highlight that mortar aggregates significantly reduce thermal mismatch and permeability, while PP fibers enhance permeability through the formation of vapor release channels. These findings provide critical insights into optimizing concrete materials for fire resistance in safety-critical applications.

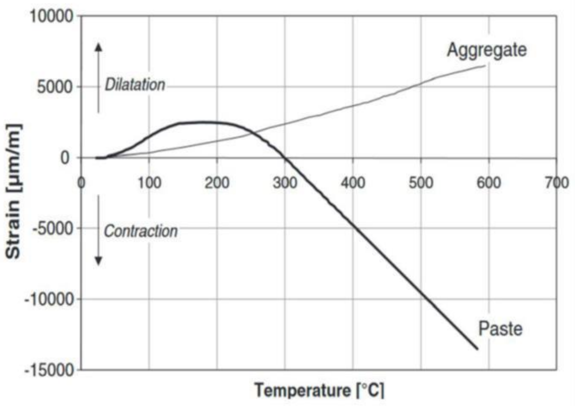


Figure 1: Differences in thermal strains of aggregates and cement paste [17]

2 EXPERIMENTAL PROGRAM

2.1 Materials

Cement was CEM III/A 52.5 L CE PM-ES – CP 1 NF from Heming provided by Eqiom. Siliceous filler from Sibelco was used as a filler, it is composed of 99.1% of SiO2. Siliceous sand 0/1 and calcareous aggregates 6.3/10 are commercially supplied by Durruty, a producer operating quarries near Bayonne, France. Mortar aggregate 6.3/10 was produced by crushing and sieving hardened mortar. To obtain fluidity of the material, superplasticizer SIKA Viscocrete Krono 26 is used. Polypropylene fibers are commercially available from Baumhüter under the commercial name Euro fibers. The fiber had a length and diameter of 18 mm and 32 µm.

Concrete containing calcareous and mortar aggregates with and without fibers were cast:

- C1-0 = concrete containing calcareous aggregate
- C1-18/32 (0.5) = concrete containing calcareous aggregate and fibers
- C1MA = concrete containing mortar aggregate
- C1MA-18/32(0.5) = concrete containing mortar aggregate with fibers.

Table 1: Concrete mix design

Materials	Mixes (kg/m^3)				
	Mortar	C1-0	C1 18/32-0.5	C1MA	C1MA 18/32-0.5
Cement	500				
Water	200				
Filler	120				
Sand	1557	623			
Gravel	-	945			
Superplasticiser	10	3.75			
Fiber 18/32	-		0.5	-	0.5

2.2 Mixing protocol and curing conditions

Coarse aggregates, filler, cement, and fine aggregates are placed in the mixer and mixed for 2 minutes. When the machine is stopped, water with a superplasticizer is added. The mixing continues for 2 minutes and the machine is stopped. Finally, polypropylene fibers are dispersed manually into the fresh mix and mixing for an additional 2 minutes is done. All the samples are cast (see Fig. 2) and demoulded after 24 hours and cured in water for 59 days.

(a) (b)

Figure 2: Images of a) mixing and b) casting of concrete

2.3 Water absorption coefficient of mortar aggregates

The water absorption coefficient of mortar aggregates was determined according to the NF EN 1097-6 standard. The water absorption coefficient is evaluated with the following equation:

$WAL24 = M_{\underline{1}}(24hM_4) - M_{\underline{4}} \times 100$ (1) With

$M_1(24h)$ = mass of saturated and superficially dry aggregates after 24 h of saturation

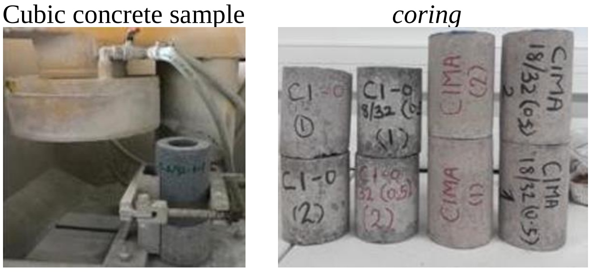
M_4 = mass of dry aggregates

The water absorption coefficient of mortar aggregates is 8,1 %.

2.4 Preparation of samples for radial permeability test

Radial permeability test was performed on hollow cylindrical samples. The sample preparation and procedures involved the coring of a cubic concrete sample of 15 x 15 x 15 cm^3 to a hollow cylindrical sample. The top and bottom faces were then ground to ensure flatness and parallelism of both faces. The final sample geometry of the sample has an internal and external radius of 2.85 cm and 5.50 cm respectively and a height higher than 15 cm. Samples were dried at 80°C up to mass stabilization. Steel inox plates are glued on the tested sample to seal the sample and prevent gas leakage during the permeability test. Before gluing, the surface of the plates was cleaned with acetone to remove dust and other impurities and lastly, the samples were cured at 80°C to harden the glue. All stages of specimen preparation can be seen in Fig. 3.

Cubic concrete sample *coring*



Grinding Concrete samples

Gluing Glued steel plates

Figure 3: Preparation of samples for radial permeability test

2.5 Heating and Testing Protocol

Residual radial permeability measurements are performed after heating to 80°C (reference temperature), 150°C, 200°C, 300°C and 450 °C at room temperature. The heating and cooling of the furnace was programmed to a 2 °C/min and a stabilization duration of 3 hours.

The same samples (2 for each mix) are used for all the target temperatures. For the testing, the bottom plate has a borehole to which a connector for the gas flow with a tube is fixed. The test sample and support sample are compressed uniaxially with a load required to counteract the injection pressure, but no more, to prevent cracks from reclosing. The load necessary for each injection pressure is presented in Table 2. The steady-state flow of the gas is achieved within 10 to 15 minutes. The test principle and the test in progress can be seen in Fig. 4 and 5.

Table 2: Injection pressure P_i and required compressive load

P absolute (bar/MPa)	Applied load (kN)
1 / 0.1	0.95
1.5 / 0.15	1.45
2.0 / 0.2	1.9
2.5 / 0.25	2.375
3.0 / 0.3	2.85

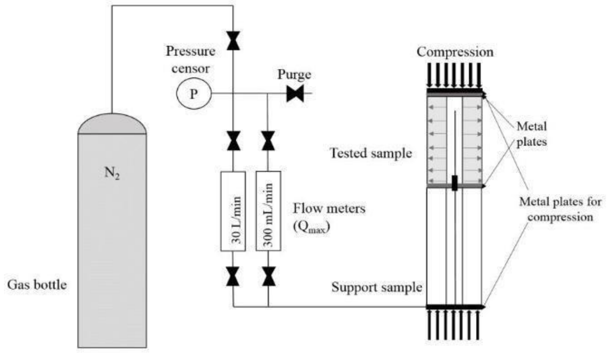


Figure 4:Scheme of experimental setup

Figure 5: Test in compressive press

4 RESULTS AND DISCUSSION

The results of the experiments are shown in Fig. 6 and 7. Fig. 6 with a logarithmic scale shows the evolution for the lowest temperatures and Fig. 7 shows more accurately the results for the highest temperature. The graphs reveal good reproducibility and fairly low dispersion. As expected, an increase in the intrinsic permeability of all concrete samples with temperature rise can be highlighted. The effect of temperature is clearly different for concrete with calcareous aggregate (C1-0) and concrete with mortar aggregate (C1MA) and when no polypropylene fibers are present.

Concrete containing mortar aggregate had lower intrinsic permeability in contrast with C1-0 concrete and this permeability difference increases with the temperature rise. Tomography scans were conducted on these concrete samples at different temperatures and no visible cracks were observed even at higher temperatures on C1MA concrete samples (see Fig. 9). This could be attributed to the lower thermal mismatch in this concrete type. Cracks in concrete with calcareous aggregate became visible at 300°C and were more pronounced at 450°C, as illustrated in Fig. 8.

All concrete samples containing fibers had a higher permeability at 200 and 300°C, with a more significant increase between 150°C and 200°C in contrast with concrete samples without fibers. This is due to the creation of channels and microcracks in the concrete corresponding to the fibers melting occurring at around 170°C.

At 200 °C, the influence of the network of channels due to fiber melting is very high in permeability. At 300 °C, the thermal mismatch becomes significant according to the permeability. The permeability of C1-0 remains lower than for C1-18/32. This highlights the combined effect of the network of channels corresponding to molten fibers and the network of cracks linked to thermal mismatch. At 450°C, the effect of thermal mismatch becomes predominant. The permeability of C1-0, with no fibers, becomes as high as that of C1-18/32 with calcareous aggregates and fibers, while C1MA-18/32 with mortar aggregates and fibers remains lower.

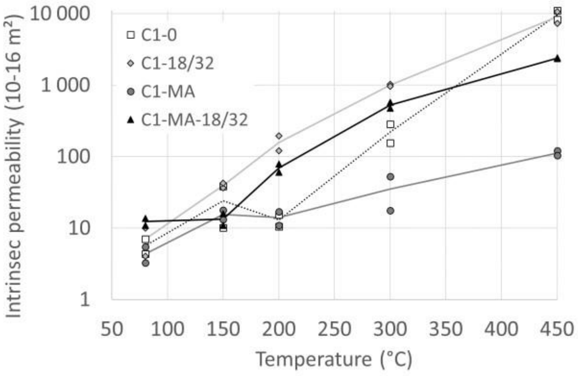


Figure 6: Intrinsic permeability vs. temperature

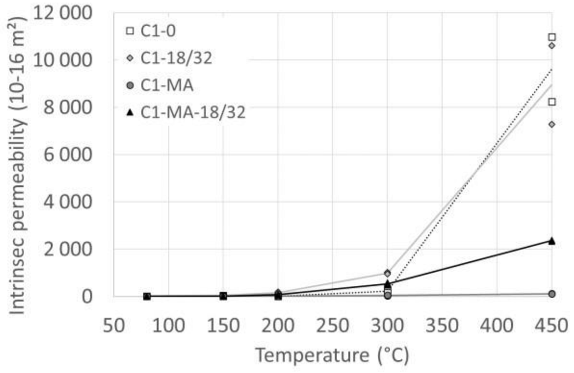


Figure 7: Intrinsic permeability vs. temperature

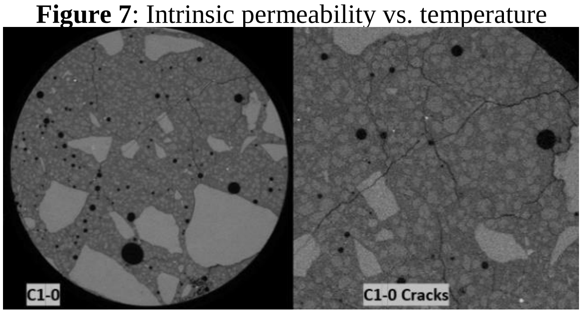


Figure 8: Images of C1-0 samples after 450°C heating

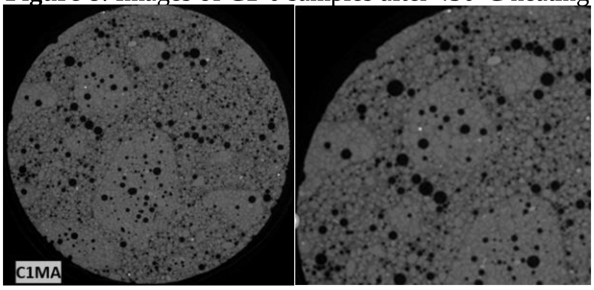


Figure 9: Images of C1MA after 450°C heating

5 CONCLUSION

The results from this study offer a deeper understanding of the influence of polypropylene fibers and their behaviour under high temperatures.

Polypropylene fibers are effective in significantly increasing permeability, and thus reducing the risk of spalling, between 150 and 200°C even in the case of aggregates with thermal expansion properties close to those of cement paste (mortar aggregate). The effect of thermal mismatch (difference in thermal expansion between cement paste and aggregates) becomes significant at 300°C and predominant at 450°C. At these temperatures, the risk of thermal instability (spalling) is therefore reduced by thermal mismatch, but this also leads to the formation of numerous cracks which degrade the mechanical properties of the concrete.

This work could be extended with other fiber dosages and using aggregates with other thermal expansion properties.

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