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Considering Environmental Effects on Porous Concrete Applications: An Experimental Investigation

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Abstract

Urban areas worldwide grapple with ecological disruption due to overpopulation, exacerbated by impermeable concrete surfaces that hinder rainwater absorption, curb plant growth and foster urban heat islands. Innovative porous concrete applications were pioneered in developed countries in recent times, offering alternative solutions albeit with limitations in strength (typically less than 20MPa). These include pavement systems (e.g. sidewalks, bike paths, parking lots), flood control infrastructure, green roofs and decorative / landscaping features. This experimental study investigates engineering properties of porous concrete mixes, suitably designed for harsh climatic conditions, with the incorporation of admixtures. A series of destructive & non-destructive tests were conducted at different ages of the concrete specimens. Test results were analysed and compared to conventional concrete to evaluate the potential benefits of using porous concrete in Scotland. This research makes a valuable contribution to the existing body of knowledge on porous concrete and provides data of direct applicability to designers and contractors so that they make more informed decisions about porous concrete applications, while considering environmental effects.

Keywords: Porous Concrete; Mechanical Properties; Sustainable Construction; Permeability; Durability; Freeze-Thaw Resistance

1. Introduction

Porous concrete, also known as no-fine aggregate or gap-graded concrete, has a history dating back to the 19th century in Europe (Francis, 1965). Post-World War II, porous concrete spread worldwide, driven by its reduced cement paste requirements compared to traditional concrete (ACI, 2006). It found early use in various applications such as retaining walls and prefabricated panels, extending later to pavements for driveways and parking lots, residential streets, alleys and other low-volume roads (Tennis et al., 2004).

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Impermeable surfaces like concrete and asphalt have exacerbated urban runoff and drainage system overload (Volder et al., 2009). Porous concrete was developed to mimic natural drainage processes, utilizing carefully selected aggregates and optimized mix designs to achieve permeability without compromising structural integrity (Xu et al., 2018, Mohd Yusak et al., 2014). It is an eco-friendly choice for effective and sustainable stormwater management, characterized by minimal sand content and an open-cell structure that facilitates rainwater filtration into the underlying soil. Studies indicate that porous pavements effectively reduce runoff volumes, enhance stormwater management, and alleviate strain on drainage systems (Xie et al., 2019, Bean et al., 2007). Stormwater runoff, which is known to transport pollutants into rivers and streams, can be mitigated through porous concrete, reducing the need for conventional stormwater management systems and costly irrigation (Göbel et al., 2007, Barrett et al., 1998). Increased water infiltration also addresses water scarcity concerns (Ferguson, 2005).

Traditionally, porous concrete was not used in heavy traffic areas due to limitations related to strength, durability and maintenance. It is promoted though as a drainable base or surface material due to its noise reduction and water absorption properties, also improving safety and cruise quality (Sanchez-Mendieta et al., 2021). Indeed, porous concrete offers noise absorption, making it quieter for driving (Olek et al., 2003) and also enhances skid resistance due to its rapid stormwater removal capability (Kevern et al., 2011, Kevern, 2006).

The mechanical properties of porous concrete, including compressive, flexural, and tensile strengths, are crucial for its suitability, especially in pavements subjected to traffic loads (AlShareedah and Nassiri, 2021). A significant limitation is its lower compressive and flexural strength compared to regular concrete. Porous concrete relies primarily on the interaction between cement paste and coarse aggregate for strength. Its high porosity reduces both compressive and flexural strength, with conventional porous concrete strength ranging from 800 to 3,000 psi, unlike typical pavement concrete with strengths of 3,000 to 4,000 psi (Tennis et al., 2004, Kosmatka et al., 2002).

In such mixes featuring a high level of interconnected macroporosity, permeability - determined by voids and interconnectedness - plays a significant role in managing stormwater (Shan et al., 2022). Aggregate choice, cementitious materials and admixtures play pivotal roles in determining permeability, strength and durability (Tennis et al., 2004, Kosmatka et al., 2002). Gap-graded aggregates, composed of particles of different sizes, create the interconnected void structure essential for effective stormwater management (Ghafoori and Dutta, 1995).

Proportions of aggregate, cement and water must be carefully balanced to attain the desired porosity and strength. Porous concrete mixtures generally feature lower cement content and a higher void ratio than traditional concrete mixes (ACI, 2010). The water/cement ratio should be optimized to ensure workability and hydration without excessive porosity and potential durability issues (Yang and Jiang, 2003). Other additives like pozzolans or supplementary cementitious materials enhance strength while reducing cement content for a more sustainable mix (Tennis et al., 2004).

The durability and environment effects of porous concrete are closely tied to factors such as the degree of saturation and exposure to freeze-thaw conditions, although limited research has addressed these aspects (Elizondo-Martínez et al., 2020). In regions affected by fluctuating temperatures, frequent freeze-thaw cycles, precipitation and the corrosive effects of de-icing salts, the durability and performance of concrete pavements and structures are impacted. The use of de-icing salts exacerbates chemical reactions within concrete, increasing porosity and weakening structures. Proper concrete mix designs, construction techniques and maintenance are essential to address these challenges (Tennis et al., 2004, Broomfield, 2023).

These considerations are very relevant to the potential use of porous concrete applications in Scotland, the country of interest for this study, where significant challenges to concrete infrastructure, particularly roads and driveways, are due to adverse weather. Suitably designed porous concrete can support managing stormwater runoff, reducing flooding and enhancing pavement durability. Porous concrete is especially valuable in areas with heavy rainfall (ACI, 2010, FHWA, 2012). Successful implementation of porous concrete in Scotland requires consideration of regional soil conditions, design standards and maintenance specifications. Proper design and construction practices, including aggregate gradation, thickness, and compaction, are essential to achieve the desired permeability and structural performance (FHWA, 2012).

To address aspects of the potential use of porous concrete in Scotland, in terms of stormwater management, urban planning and sustainability goals, the aim of this experimental investigation is to experimentally assess selected mix designs and evaluate critical engineering parameters under realistic conditions (requirements, climate). To achieve that, strength and permeability measurements at typical times and temperature conditions were determined as per the following objectives:

1. Determination of the compressive, flexural, tensile strengths and permeability of porous concrete samples cured for 7 and 28 days,
2. Incorporation of experimental choices reflecting weather condition effects,
3. Discussion of the applicability of the investigated mixes for sustainable infrastructure projects in Scotland.

2. Experimental Program & Mix Design

The experimental study commenced with exploration of trial mixes and consultation of the relevant literature, to then focus on 2 main design mixes, with their constituents and properties been investigated via a series of material and specimen tests (Fig. 1). Both mixes (Mix 1 - M1 and Mix 2 - M2) comprised cement, mostly coarse aggregate, clean water, polypropylene and cellulose fibres (see elements 1-6 in Table 1) as well as admixtures (see elements 8-10 in Table 1). In addition to these, the second mix (M2) contained a water–reducing admixture and a latex polymer additive (see elements 7 and 11 in Table 1).

Specimens were prepared in the Heavy Structures Laboratory at Edinburgh Napier University and were subjected to a series of non-destructive and destructive tests following the relevant British standards or well-established experimental approaches as documented in the literature. Destructive tests were performed at 7 and 28 days of curing, with some repetitions after a 5 days freeze-thaw cycle regime (testing at 33 days). For a given set of materials, strength and permeability can be competing factors in the design process and this was taken into account when considering testing options – with the experimental plan mainly focusing on two types of permeability tests (variable/falling head and constant head) and the compressive strength tests, complemented by tests measuring the tensile and flexural strengths of our concrete specimens. While compressive strength is important for quality control and for assessing the mechanical behaviour of porous concrete, tensile strength is an important parameter in the design of conventional pavements and flexural strength is a crucially important design factor for rigid pavements.

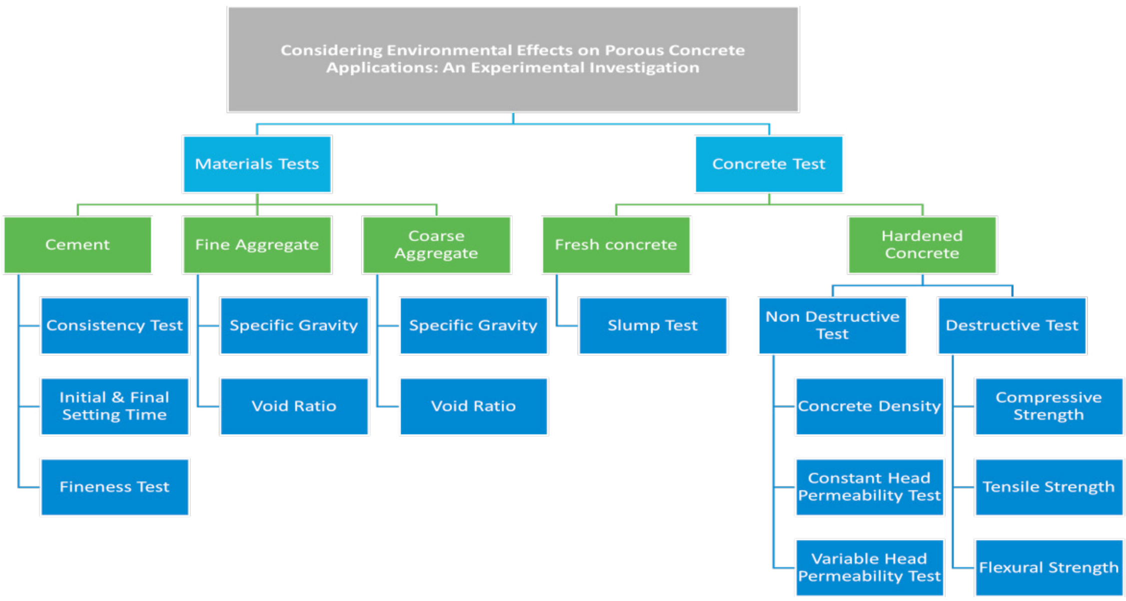

Fig. 1. Flow chart for Experimental Investigation on Porous Concrete.

Table 1. Mix design content and principles for the preparation of the two mixes under investigation.

Mix Design for Porous Concrete		
Sl.No	**Materials**	**Standard/Required Values for 1 Cubic Metre (Cum)**
1	***52.5*** Cement	380 kg/m3
2	***0/4*** Fine Aggregate	140 kg/m3
3	***4/14*** Coarse Aggregate	1440 Kg/m3
4	Clean Water	110 Kg/m3
Fibres		
5	Polypropylene Fibre	1.4 Kg/m3
6	Cellulose (Beech) Fibre	0.9 Kg/m3
Admixtures		
7	Polycarboxylate high range water-reducing admixture (HRWRA)	Recommended: 0.2 -1.5 % by weight of cement
8	Vinsol resin air-entraining agent (AEA)	Recommended: 0.1 -0.8 % by weight of cement - **2 ml /Kg**
9	Hydration-stabilizing (HS) admixture	Recommended: 0.4 -3 % by weight of cement - **8 ml /Kg**
10	Polysaccharide viscosity-modifying admixture (VMA)	Recommended: 0.1 -1.0 % by weight of cement- **3 ml /Kg**
11	2% solids triethanolamine latex polymer additive (LX)	9 ml /Kg or 31 Kg/m3

3. Experimental process and results

3.1. Non-Destructive Tests (Slump, Density & Permeability)

Initial tests studied the consistency and density of the mixes, with resulting values measured within the expected range. Slump tests were performed in accordance with the BS EN 12350-2:2019 with results falling within the acceptable slump range of 0-20 mm as specified in the mix design and M2 being slightly stiffer and less workable than M1 (slump 3mm and 5mm respectively). Density measurements were performed following the BS EN 12390-7:2019 with insignificant differences in recorded values between the two mixes at 28-days (M1:2260kg/m^3 and M2: 2290kg/m^3).

Permeability tests help assess the effectiveness of porous concrete in facilitating storm water infiltration and drainage. Two established permeability measurement methods were applied (Fig. 2), the constant head test (submerged water permeability) and the variable/falling head test (un-submerged water permeability) (Pieralisi et al., 2017). For the first case, a cylindrical specimen is placed in the apparatus and water is continuously supplied to the top of the specimen at a constant head (pressure) while the flow rate of water passing through the specimen is measured. For the falling head test, water is allowed to flow through the specimen under gravity. The water level is measured over time as it gradually falls due to water going through the porous concrete and the permeability is calculated using the falling head permeability equation, which considers the flow rate, cross-sectional area and change in water level. The experimental set-up is secured on the wall and the specimen is held in place in the centre of the two tubes with waterproof adhesive aluminium tape on both ends, and then fully wrapped in waterproof adhesive aluminium, rubber membrane and rubber amalgam tape to create lateral pressure, thereby restricting lateral flow (Fig.4).

The cylindrical specimens were cast in molds of 200 mm in height and 100 mm in diameter, de-molded after 24 hours and cured for 7 days, when 25 mm was sawed off from each end of the specimens in order to avoid inhomogeneity at ends. The specimens were then cleaned with air compressor and water pressure washer (Fig. 3). Nine specimens were tested for each mix, with three repetitions each, at three different ages – 7, 28 and 33 days (after a five days freeze-thaw cyclic regime at -26ºC).

Average results (Fig. 4) indicate insignificant variations in measurements between the two methods and consistently higher permeability for M2, attributed to the slightly modified pore structure due to the admixtures. Both mixes experienced reduced permeability when tested after the freeze-thaw cycles, by 17% for M1 and just above 18% for M2. The susceptibility of porous concrete to freeze-thaw functional and longer-term damage, is a common concern requiring further investigation.

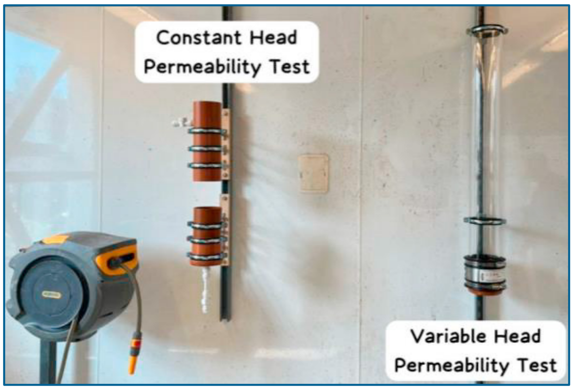

Fig. 2. Experimental set-up for two types of permeability tests

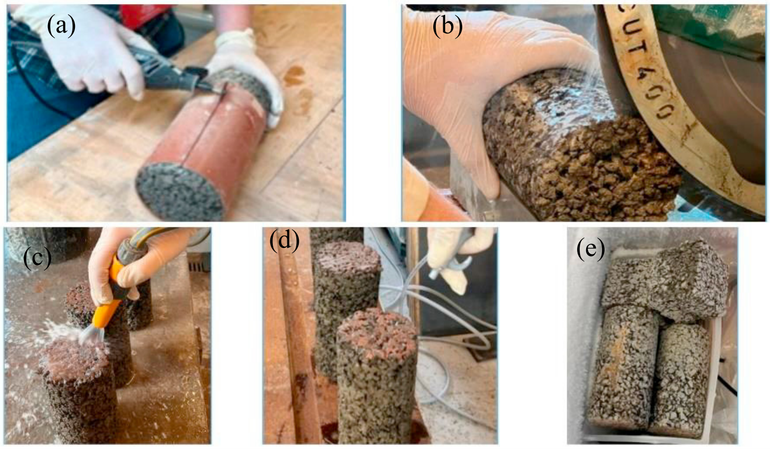

Fig. 3. Stages of specimen preparation for permeability testing: (a) de-molding; (b) cutting; (c-d) water- and pressurised air-cleaning; (e) freezing

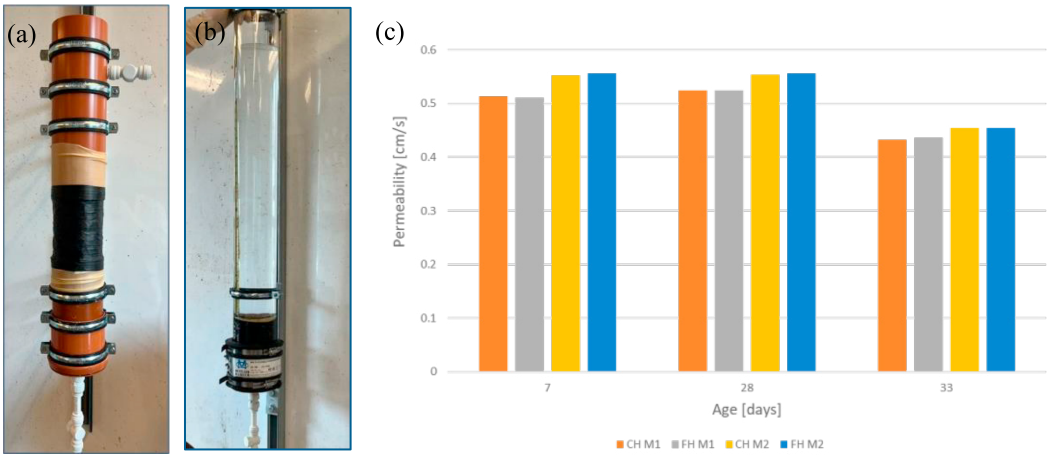

Fig. 4. (a) Constant Head {CH} Permeability Test; (b) Falling Head {FH} Permeability Test; (c) Permeability results for M1, M2 and both methods (CH, FH)

3.2 Destructive Tests (Compressive, Tensile & Flexural Strength):

The compressive strength test was performed in accordance with BS EN 12390-3:2019. Figure 5 presents experimental results from compression tests on cubic specimens of both mixes, for 3 different ages. Compressive strength variations with age are compatible with the hydration process mechanisms and clearly influenced by the presence of admixtures. Mix 2 contains a water-reducing admixture and an additive that improves overall bonding by increasing the adhesion between cementitious materials and aggregates, which explains the earlier development of strength and the enhanced performance compared to Mix 1. Compressive strength requirement for relevant ordinary construction projects is set at 20MPa (BS 8500-1:2015 for roads and BS 8102:2009 for below ground structures) which is achieved by Mix 2 from an early age and marginally by Mix 1 at 28 days.

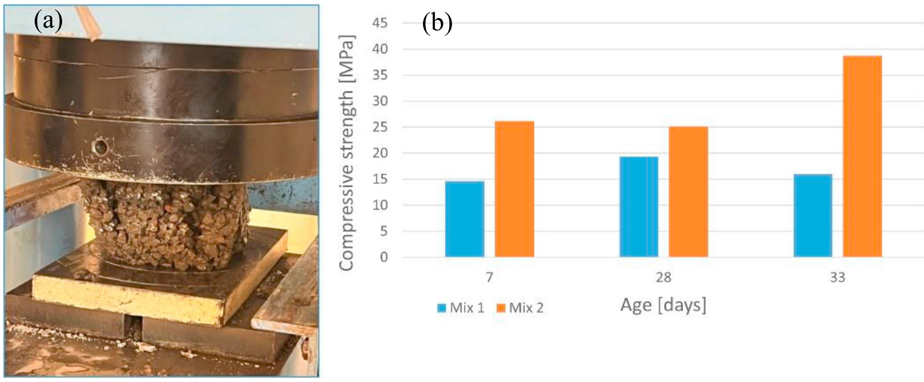

Fig. 5. (a) Compression test failure mechanism; (b) Compressive strength results for M1, M2

Splitting tensile tests were performed on 100mm x 100mm x 100mm cube specimens (BS EN 12390-6:2009) and flexural tests on 500mm x 100mm x 100mm beams (BS EN 12390-5:2019). Both 3 Point-Bending (3PB) and 4 Point-Bending (4PB) tests were used to gain further insight into the mechanical properties of our mixes for a wider range of applications. Mix 2 consistently outperforms mix 1, with this attributed to the high-range water-reducing admixture (HRWRA) and latex polymer additive (LX), unique to this mix, which collectively contribute to reduced water content, improved flowability, enhanced cement hydration, minimized porosity and superior adhesion and cohesion. The tensile strength represents the 7.5% of the compressive strength for Mix 1 and the 10% for Mix 2. All results are within expected ranges for porous concrete and confirm that both the tensile and the flexural strengths are positively correlated with the compressive one (Fig. 6,7).

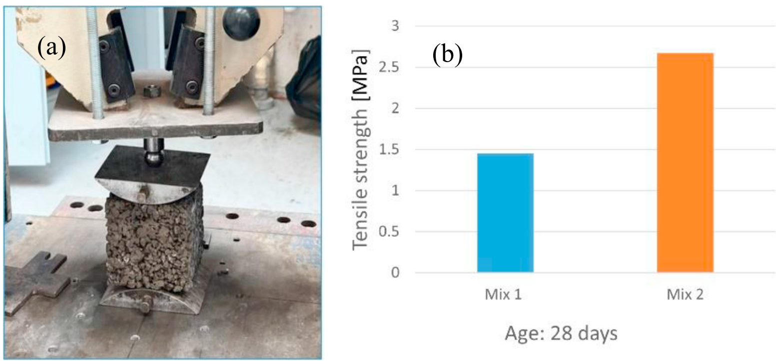

Fig. 6. (a) Tensile test failure mechanism; (b) Tensile strength results for M1, M2

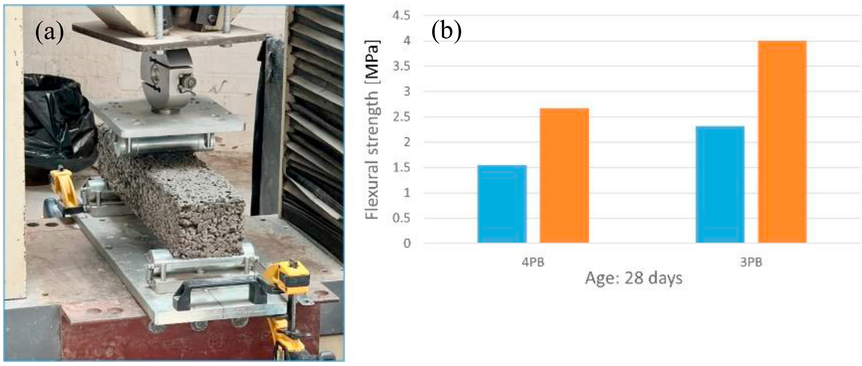

Fig. 7. (a) 3 Point-Bending test; (b) Flexural strength results for M1, M2

4 Discussion

The performance of two porous concrete mixes was experimentally studied to check their viability for applications in Scotland's infrastructure, particularly for sustainable drainage systems. HRWRA and LX admixtures improve performance producing a mix that exhibited superior workability and strengths, as well as enhanced permeability. There are also indications for improved durability as a result for an improved freeze-thaw resistance because of their use, but the scale of this study does not justify definitive conclusions.

The mix design was considered satisfactory, and results reinforced the potential of admixtures especially with respect to strength development. Further adaptations of the design can enhance suitability with respect to other categories of road infrastructure and domestic applications, and provide flexibility for local environmental needs. Suggested additional considerations as part of further research extend to cover: long-term durability tests, including freeze-thaw cycling and exposure to aggressive environments for an extended period of time to assess the concrete's performance and maintenance needs over time scales comparable to a project's service life; microstructural analysis with advanced optical techniques for the classification and interpretation of failure modes; mix design with optimised dosage and combinations of admixtures; field trials with porous concrete installations in real-world projects that will enable us to promote such solutions outside a laboratory environment.

Porous concrete presents significant environmental benefits that could compensate for its lower unit weight, modulus of elasticity and strengths, all presenting some limitations with respect to structural applications. The findings collectively emphasize the potential of porous concrete for diverse applications in Scotland. They contribute to the existing body of knowledge on porous concrete and provide data of direct applicability to designers and contractors so that they make more informed decisions about porous concrete applications, while considering environmental effects.

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