

**Enhancing the spacer-concrete interface
for durable structures**

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Declaration

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Xi Chen

Abstract

Cementitious spacers are commonly used in concrete construction. A wide variety of spacers is available. However, the quality of these spacers and their potential impact on the long-term durability of concrete structures are not well understood. Available research on cementitious spacers have shown that the spacer-concrete interface is more porous and microcracked than the bulk concrete. This accelerates penetration of external aggressive species that could be detrimental to concrete durability. Yet very little fundamental research has been carried out on improving the spacer-concrete interface. This study aims at investigating the performance of cementitious spacers and their effects on concrete microstructure, mass transport properties and durability. Additionally, the study aims to develop novel methods to enhance mechanical and/or chemical bonding between spacers and concrete, and therefore improve the long-term durability of concrete structures.

Cementitious spacers from top European manufacturers were examined for their dimensional, mechanical and durability properties, and their effects on concrete mass transport properties. Great variations in performance were observed between different spacers, especially in terms of porosity, water absorption and carbonation resistance. Some spacers were already carbonated at the time of delivery prior to usage. The incorporation of these spacers in concrete increased mass transport (e.g. oxygen diffusivity, oxygen permeability and water sorptivity) to various levels. Oxygen permeability was found to be most severely affected. This is attributed to the weak spacer-concrete interface that is highly porous and microcracked.

New methods were developed to improve the spacer-concrete interface by enhancing their mechanical and chemical bonding. These include producing novel spacers with rough surface texture, with exposed fibres and/or reactive cementitious particles. Fibre-reinforced mortars (with three fibre types, two fibre lengths and two fibre volume fractions) and slag-based mortars (with two water/binder ratios and three slag replacement ratios) were investigated as alternative materials for producing cementitious spacers. Compressive strength and mass transport properties of the spacers were tested at different curing ages. Composite cylindrical samples containing half spacer and half concrete were prepared and tested for bond strength, mass transport properties, fluorescent epoxy impregnation, carbonation resistance and microstructure. These were compared against samples with conventional spacers.

Results showed that the developed cementitious spacers achieved good compressive strength and low mass transport properties. Fibre-reinforced cementitious spacers produced with the new method decreased crack initiation and propagation at the spacer-concrete interface, and this led to lower mass transport properties, especially oxygen permeability. Cementitious spacers containing high slag replacement and low water/binder ratio also improved the spacer-concrete bonding. This was evident from the increased bond strength, decreased mass transport properties and denser microstructure at the spacer-concrete interface.

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Notation

Abbreviations

AC	Anhydrous cement
BSE	Backscattered electron
COV	Coefficient of variation
C-S-H	Calcium silicate hydrate
C-H	Calcium hydroxide or portlandite
DB	De-bonding between spacer and concrete
DIC	Digital image correlation
EDX	Energy-dispersive X-ray microanalysis
FC	Fracturing of the concrete
FS	Fracturing of the spacer
GF	Glass fibre
GGBS	Ground granulated blast-furnace slag
HP	Hydration products
ITZ	Interfacial transition zone
NC	Normal concrete
PC	Portland cement
PPF	Polypropylene fibre
RFDA	Resonant Frequency and Damping Analyser
RH	Relative humidity
SCM	Supplementary cementitious material
SEM	Scanning electron microscopy
SF	Steel fibre
SHCC	Strain-hardening cementitious composite
UHPFC	Ultra-high performance fibre concrete

w/b	Water/binder ratio
w/c	Water/cement ratio

Roman letters

a	Constant for fitting
A	Cross-section area of sample (mm ²)
b	Width of sample (mm)
C_1	Mean concentration of oxygen in the nitrogen stream at 1 bar (m ³ /m ³)
C_2	Concentration of oxygen in the oxygen stream at 1 bar (m ³ /m ³)
d	Diameter of the reinforcement being supported by spacers
D	Diameter of sample (mm)
D^*	Diffusion coefficient (m ² /s)
D_c	Impregnation depth through concrete (mm)
D_{IT}	Impregnation depth through spacer-concrete interface (mm)
d_s	Average depth of sample (mm)
D_s	Impregnation depth through spacer (mm)
F	Maximum applied load (N)
f_{IS}	Bond strength obtained through direct tensile splitting test (MPa)
$f_{IS,dic}$	Bond strength obtained through digital image correlation test (MPa)
g	Local acceleration due to gravity (m/s ²)
G_0	Percentage of oxygen in the initial nitrogen stream (0.004%)
G_f	Energy absorbed at failure stress of fibre-reinforced spacer-concrete composite samples (kJ/m ³)
G_I	Percentage of oxygen in outflow stream
G_u	Energy absorbed at ultimate stress of fibre-reinforced spacer-concrete composite samples (kJ/m ³)
H	Capillary rise (m)
i	Cumulative absorbed water per unit area (g/m ²)
k_g	Apparent permeability coefficient (m ²)
k_{int}	Intrinsic permeability coefficient (m ²)

L	Span length (mm)
m_c	Mass of the sample at conditioned state (kg)
m_s	Mass of the sample at vacuum saturated state (kg)
n	Number of discrete measurements
N_f	Average number of fibres exposed to the surface of fibre-reinforced spacers in direct tensile splitting test
$N_{f,dic}$	Average number of fibres exposed to the surface of fibre-reinforced spacers in digital image correlation test
P_1	Pressure of oxygen stream (bar)
P_1^*	Absolute pressure on the inlet face (N/m ²)
P_2	Pressure difference between the oxygen and nitrogen stream (bar)
P_2^*	Absolute pressure on the outlet face (N/m ²)
p_i	Maximum peak height in each sampling length
P_m	Mean pressure of the inlet and outlet streams (m ²)
Q	Flow rate (m ³ /s)
Q_d	Oxygen diffusion rate at 1 bar
R	Modulus of rupture (MPa)
R_1	Flow rate of nitrogen stream (mL/min)
R^2	Coefficient of determination for linear regression
R_2	Flow rate of oxygen stream (mL/min)
R_a	Average roughness
R_p	Radius of the pore (m)
R_{pm}	Mean peak height
R_q	Root-mean-square roughness
R_{vm}	Mean valley depth
$R_{z(DIN)}$	Mean peak-to-valley height
$R_{z(ISO)}$	Ten points height
S	Sorptivity coefficient (g/m ² min ^{0.5})
t	Time (s or min)
T	Thickness of sample (mm)
V	Volume of the sample (m ³)

v_i	Maximum valley depth in each sampling length
z_i	Amplitude of each measurement

Greek letters

β	Constant for a given material and gas
γ	Surface tension of the liquid (N/m)
η	Viscosity of the liquid (N/m ² ·s)
η_v	Gas viscosity (2.02×10^{-5} Ns/m ² for O ₂ at 20°C)
θ	Contact angle
ρ	Density of the liquid (kg/m ³)
ρ_w	Density of water at 20°C (1000 kg/m ³)
φ	Accessible porosity (%)
$\varnothing$	Diameter (mm)

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Chapter 1 Introduction

1.1 Research background

Concrete plays an important role in construction because of its high compressive strength, good sustainability and versatility, easy availability, and low cost. Structural concrete is always reinforced with embedded steel as the two materials complement each other and develop optimal resistance to different external actions. However, reinforced concrete structures gradually degrade when subjected to different environments, of which reinforcement corrosion is a dominant degradation mechanism (Ahmad, 2003; Green, 2020). To protect reinforcing steel from corrosion, a minimum cover depth of concrete should be provided according to the exposure environment and expected service life. The concrete cover also protects reinforcements from fire and provide adequate embedding stress to prevent slippage, and thus help guarantee the long service life of reinforced concrete structure (BS EN 1992-1-1:2004+A1:2014, 2014).

Incorrect concrete cover in construction is often due to the failed positioning of reinforcement during concreting (Naotunna et al., 2022; Bacharz et al., 2019). This includes not only the insufficient concrete cover but also excessive concrete cover, which could lead to the reduction in bending resistance and increase in crack width (Lin et al., 2017; Li et al., 2021). Prior to 1989, there was no published national guidance on the placing and positioning of reinforcements. Site made mortar blocks, wooden blocks, pieces of bricks and some other on-site materials were commonly used to support rebar during concreting (Shaw, 2007; Alzyoud et al., 2016). In some extreme cases, no specialised supports for reinforcements were adopted as the rebar was placed into wet concrete after the concrete had been poured into the formwork. Gradually, manufactured spacers were introduced and commercially available for better control of the position of reinforcement. According to British Standard (BS 7973-2:2001, 2001), a spacer should be located at every meter (or less), or as otherwise necessary, along the length of reinforcing bars. These spacers are left permanently and become part of the structure, thus both the durability of the spacers and their effects have a huge influence on the long-term behaviour of concrete structures.

However, commercially available spacers have a great variety in terms of their material, size and shape. Plastic, cementitious materials and steel are the three basic materials used for producing spacers (BS 7973-1:2001, 2001). Plastic spacers are generally cheaper, more versatile, and easier to use. However, the intricate shape of plastic spacers could affect the compaction of surrounding concrete. Furthermore, the thermal expansion coefficient of plastic is very different from that of concrete (Ribeiro et al., 2003; Ferrier & Agbossou, 2017), and this is likely to induce microcracking at the spacer-concrete interface when subjected to temperature variation. Cementitious spacers are commonly made of mortar, concrete, or fibre reinforced concrete, and can be classified as block spacers and line spacers (Alzyoud, 2015). Block spacers provide single, double, and even triple covers, but normally have embedded steel or plastic clips or wire to fix reinforcements. Line spacers are usually manufactured as one metre straight or curved bars with square, round, or rectangular cross sections. Block cementitious spacers may also increase the risk of poor compaction around the clips or wire. In addition, cementitious spacers are made from various ingredients (such as different binders, aggregates and additives) and mix composition. Their microstructure and properties are diverse and therefore could lead to very different performance. Steel spacers are classified as single wire or continuous chairs, and are mainly used in slabs to support mesh reinforcements. They can corrode and pre-coating is sometimes necessary as additional protection (ACI 315-99, 1999).

The first national guidance on spacers in the UK was published in 1989 and this was then superseded by the British Standard (BS 7973-1:2001, 2001) in 2001. The material, dimension, strength, deformation and placement of spacers are regulated in this standard. However, no specific guidance on durability or performance testing for durability of spacers are provided. Other guidance on spacers elsewhere includes (ACI 315-99, 1999) “Manual of standard Practice for Detailing Reinforced Concrete Structures” and Concrete Reinforcing Steel Institution “Placing Reinforced Concrete Manual”(CRSI, 2011) provide little guidance related to durability except for coating requirements for steel spacers. There are limited specifications for cementitious spacers in terms of composition, porosity and resistance to ingress of aggressive species. There is also a lack of test methods or testing requirements to ensure the performance of spacers in concrete.

A search on available literature from spacer manufacturers worldwide found limited information on the durability performance of spacers. Some manufacturers claim that their spacers are at least of equal quality as the concrete used in construction, but little or no test data

can be found to support these claims. Alzyoud et al. (2016) investigated the effects of spacers on the properties of concrete. It was shown that spacers increase mass transport of concrete due to the porous nature of the spacer-concrete interface. The interface was found to have higher water/cement ratio and higher de-bonding microcracks compared to the bulk concrete. Muslim (2020, 2021b) found that the presence of spacer induces a negative effect on mass transport regardless of the spacer type (vertical/horizontal) or the presence of supplementary cementitious materials (SCMs). However, altering the geometry, shape and orientation of the spacers may increase bond strength and potentially decrease mass transport properties (Muslim et al., 2021a). It is also worth noting that only two types of cementitious spacers from the same manufacturer were investigated in the aforementioned studies.

There is a general lack of understanding of the properties of spacers and their influence on long-term performance of concrete structures. Therefore, the performance of commercially available spacers, especially cementitious spacers, and their effects on the microstructure, mass transport properties and durability of the concrete cover zone should be investigated. This will provide a valuable reference for existing structures and future construction. More importantly, there is a great need to develop new spacers with improved properties and new methods to enhance the characteristics of the spacer-concrete interface.

1.2 Aim and objectives

The aim of this research is to understand the performance of cementitious spacers and their effects on concrete durability, and to develop new improved cementitious spacers that could provide better chemical and mechanical bonding with concrete, and thereby improving the long-term durability of concrete structures. The study will first investigate the properties of available cementitious spacers to fill the knowledge gap that concerns the quality of spacers used in the industry. Then, the study will focus on developing methods to eliminate the weak interface between spacer and bulk concrete. The key objectives are listed as follows:

- 1) Obtain a range of samples of cementitious spacers from major manufacturers. Develop laboratory methods to test dimensional, mechanical and durability properties of these cementitious spacers. Embed these spacers into concrete and evaluate their effects on concrete mass transport properties.
- 2) Develop methods to produce spacers with surfaces that will bond better with surrounding

concrete, either mechanically or chemically. These may include methods that modify surface texture, or expose unreacted cement particles and fibres on the surfaces of spacers.

- 3) Investigate the potential of fibre reinforced cementitious composites as a means to increase the bonding and reduce microcracking between spacer and concrete. Compare the effects of fibre type, length and volume fraction and processing conditions, and optimise the design of the fibre-reinforced cementitious spacer.
- 4) Investigate the potential of using GGBS as an alternative binder to produce spacers that would maintain a reactive surface to bond with concrete. Determine the composition and processing conditions to optimise the bond strength and reduce mass transport properties of the spacer-concrete composites.
- 5) Perform a series of assessment (e.g. strength, durability, microstructure) to evaluate the performance of the developed spacers against conventional cementitious spacers.

1.3 Thesis outline

The thesis is divided into 8 chapters. Chapter 1 outlines the motivation, general background, objective and scope of this study. Chapter 2 provides a literature review on spacers, their properties, regulations regarding their applications and previous research about their effects on concrete durability. It also reviews topics relevant to the objectives of this thesis. Chapter 3 details the main experimental approach including the materials, mix designs, developed methodology, test instrumentation and common procedures used in this thesis. Further details and particulars of some unique tests conducted in the following chapters were further elaborated in the respective chapters.

The main findings of this study are presented in the Chapter 4 to 7. There is a great variety of cementitious spacers currently available in the industry. The quality of these spacers, especially their durability, is unregulated in many places. To date, no systematic study could be found on their performance. In addition, previous studies related to the effects of spacers on concrete durability only included limited types of spacers. The effects of various cementitious spacers are not sufficiently understood currently. In Chapter 4, nine types of cementitious spacers from top manufacturers across Europe were collected. The dimensional, mechanical, and durability properties of these spacers were evaluated through a series of tests. In Chapter 5, these spacers

were embedded in concrete at two water/cement ratios. Their effects on the durability of porous and dense concrete mixtures were evaluated through a series of mass transport testing.

Results from Chapters 4 and 5 show that the use of current cementitious spacers resulted in an increase in the mass transport properties of concrete. This is attributed to the porous microstructure of these spacers and spacer-concrete interface. A large number of microscopic cracks were found inside cementitious spacers and at the spacer-concrete interface. Therefore, the main objective of Chapters 6 and 7 is to develop new spacers that are more durable and with improved spacer-concrete interface.

Chapter 6 presents an investigation on developing fibre-reinforced cementitious spacers. A new method was developed to produce spacer with exposed fibres on the surfaces, with the aim of achieving better mechanical bonding between spacers and concrete and reducing the generation of microcracks. In Chapter 7, spacers with surface reactivity were developed to improve chemical bonding between spacer and concrete. This was achieved by combining the use of high slag-replaced cementitious materials and the new spacer producing method. Bond strength, mass transport, and microstructural properties were evaluated to determine the effectiveness of these spacers.

Finally, Chapter 8 summarises the main findings of this thesis and gives suggestions and recommendations for future research.

Chapter 2 Literature review

This chapter presents a literature review on existing studies relevant to the scope of this thesis. It includes a background on spacers, regulations concerning their use and known effects of spacers on the properties of concrete. Limited research has been done on spacer-concrete interface. Therefore, literature concerning concrete-to-concrete interface, which has similarities with spacer-concrete interface, are reviewed. Basic mechanical and durability properties of concrete-to-concrete interface are presented. Main factors affecting the properties of the interface are discussed. Finally, methods on improving the interface are reviewed.

2.1 Reinforcement spacer

2.1.1 Background and categories

Reinforcement spacers, also referred to as rebar supports, chairs, bolsters, continuous runners and dowels, are components used for maintaining accurate concrete cover and rebar placement before and after concreting. They are placed between reinforcement and formwork, reinforcement and blinding, or reinforcement of different layers. Spacers are used to support reinforcement in different directions, such as horizontal rebar in slabs and beams, vertical rebar in columns and walls, and inclined rebar in tunnels and other element types.

Prior to 1960, specially produced spacers for construction did not exist. Any materials available on site were commonly used to support reinforcement (Muslim, 2018). Gradually, manufactured spacers were introduced and commercially available as a replacement. These are mainly produced either with plastic, cementitious material or steel (Alzyoud et al., 2016). Typical examples of spacers are shown in Figure 2.1.

Plastic spacers

Plastic spacers are produced with plastic of different strength grades for supporting reinforcement of various sizes. There are four types of commonly used plastic spacers in terms of their shapes: A-spacer, tower spacer, wheel (or circular) spacer and line (or bar) spacer. A-spacers and tower spacers can be used in both horizontal and vertical components. Tower spacers are capable of supporting heavier reinforcement because of their wider base, and they can also be used for double-cover applications. Therefore, they are generally used in floor slabs,

ground beams and foundations. Wheel spacers are mainly used in vertical structural elements such as columns, walls and pile cages. Line spacers are commonly used in horizontal components with heavy-duty applications or soft subbase. The large support surfaces prevent damages to insulation or soft ground (Alzyoud, 2015).

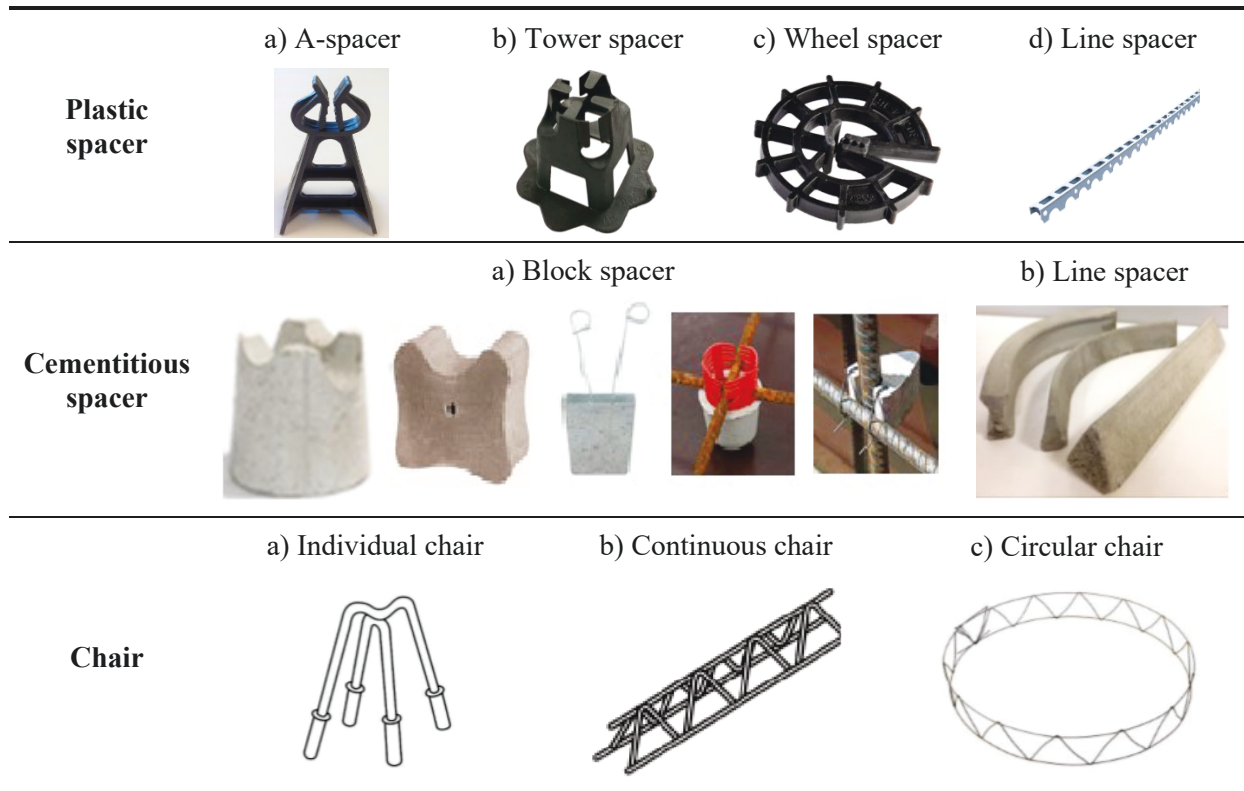


Figure 2.1 Typical types of spacers (Alzyoud et al., 2016; Muslim, 2018)

Plastic spacers are widely used in construction because they are versatile, easy to apply and cost-effective. They are generally designed with a clamping device to secure the reinforcement. Thus, they could be fixed to the reinforcement directly without the need for wire tying. However, plastic spacers are generally weaker than other spacer types and are used for supporting relatively low loads. In addition, the bond between plastic spacers and concrete is a particular concern. Plastic spacers have relatively complicated shapes, which could affect the compaction of concrete around it. The openings in plastic spacers must be large enough to allow aggregates to pass through and nestle inside (Levitt & Herbert, 1970). The coefficient of thermal expansion of plastic is more than 10 times that of concrete (Engineering Toolbox, 2003). This could cause spacer-concrete debonding or microcracking when exposed to temperature variation. In addition, plastic spacers may age under the influence of heat or

exposure to light and certain chemicals. Furthermore, they could melt and ignite at elevated temperatures (e.g. polyethylene melts at 95-105°C and ignites at 349°C) (Jiang et al., 2021; Mark, 1996) and therefore reduce the fire resistance of concrete cover, and even lead to early collapse of concrete structures such as tunnels and high-rise buildings. However, there are no recommendations in the British Standards (BS 7973-1:2001, 2001; BS 7973-2:2001, 2001) on mitigating the risks or hazards posed by plastic spacers in such situations. Concrete cover requirements for achieving sufficient fire resistance are also provided without considering the effect of embedded plastic spacers (BS EN 1992-1-2:2004+A1:2019, 2019). Little investigation has been carried out on this so far.

Cementitious spacers

Cementitious spacers are manufactured from either mortar or concrete. Fly ash, slag, silica fume or fibre are usually incorporated to improve the performance of these spacers. Cementitious spacers are classified as block (or point) spacer and line (or bar) spacer (shown in Figure 2.1). Block spacers come in various shapes and sizes fitting both vertical and horizontal elements, and they are applicable for single, double and even triple cover requirements. Most block spacers are either embedded with plastic clip, steel clip or wire, or include a hole for tie-wire. Some block spacers can be used directly without clips or wires, such as castle spacers and wheel spacers. Castle spacers are normally designed with a wide base and concave top for securing reinforcement. They are mainly used for supporting heavy-duty mesh reinforcement such as ground-floor slabs or foundations. Wheel spacers are designed with a hole in the centre for reinforcement to pass through. They are mainly used in vertical elements such as columns and piles, and horizontal elements considering the small contact with formwork (Muslim, 2018).

Line spacers are mainly used for bridge decks, slabs and heavy-duty reinforced foundations. They are manufactured in a range of shapes, with rectangular, triangular or round cross sections. Some spacers have variable cross section along their length to minimise exposure on the element surface. Curved line spacers are introduced to prevent the formation of a straight continuous weakness path along the concrete cover. Line spacers with embedded clips and wires are also available, enabling their use in vertical elements. Cementitious spacers are suitable for heavy-duty applications, and have similar coefficient of thermal expansion with concrete. However, the tying process when using cementitious spacers is time consuming.

Furthermore, cementitious spacers can degrade and crack during manufacture, storage and usage.

Steel spacers

Steel spacers are also referred to as chairs. They are commonly used to support top horizontal reinforcement or to separate vertical reinforcement in walls (BS 7973-1:2001, 2001). There are three categories of steel chairs: individual, continuous and circular chair. Individual chairs are used to support reinforcement at single location and are widely used for supporting top reinforcement in cantilever slabs without bottom reinforcement. Continuous and circular chairs are commonly used to support mesh reinforcement or to maintain equal distance between reinforcement layers. They are comprised of welded lattice wires. Continuous chairs are produced straight longitudinal, while circular chairs are normally delivered flat and formed on site (BS 7973-1:2001, 2001). Steel chairs are robust and are resistant to tipping, and they have similar coefficient of thermal expansion with concrete. However, they are vulnerable to corrosion, thus require additional protection such as coating with epoxy. The end of each chair leg shall be encased in a protective tip (such as a closed plastic sleeve) for a distance of at least 40 mm when they are used to support reinforcement off an exposed face (BS 7973-1:2001, 2001).

Guidance on spacers

Development of guidance on reinforcement spacers in Europe started relatively recently. The first national guidance on spacers in the UK is CS101 (1989) “Spacers for reinforced concrete”, published by the Concrete Society in 1989. In 2001, this was superseded by BS 7973 (2001) “Spacers and chairs for steel reinforcement and their specification”, which was the first British national standard on spacers. This provides guidance on the manufacture and application of spacers including dimensions, identification, strength and deflection requirements, fixing, tying and spacing. In addition, BS EN 13670 (2010) “Execution of concrete structures” published in 2010 also includes certain guidance on the performance and selection of spacers used in construction. Other guidance on spacers available in Europe includes Bulletin d’Information No.201 “Spacers, chairs and tying of steel reinforcement” published by the Comité Euro-International du Béton in 1990, DBV data sheet Leaflet (2011) “Spacers According to Eurocode 2” issued by the German Concrete and Construction Technology Society in 2011 and DIN 1045-1 (2008) “Structures made of concrete, reinforced concrete and

pre-stressed concrete structures - Part 1: Design and construction” issued by the German Institute of Standardization in 2008.

Formal regulations on spacers are limited elsewhere. In North America, ACI 315-99 (1999) “Details and detailing of concrete reinforcement” issued by the American Concrete Institute, “Placing reinforcing steel” issued by the Concrete Reinforcing Steel Institute and CSA A23.1-14 (2014) “Concrete materials and methods of concrete construction” issued by the Canadian Standards Association provide some guidance on spacers. In Australia and New Zealand, AS/NZS 2425 (2015) “Bar chairs in reinforced concrete - Product requirements and test methods” specifies some requirements for spacers. This is a relatively recent standard published in 2015, and it includes regulations on the strength, deflection, dimension, stability, traceability and fixing of spacers. In addition, durability requirement of cementitious spacers is also considered in this standard. However, the consideration only includes rapid chloride permeability testing. In China, JTG/T F50-2011 (2011) “Technical specification for construction of highway bridge and culvert” issued by Ministry of Transport of China in 2011 provides guidance on basic requirements and application of spacers. Regulations of spacers listed in each standard are summarised in Table 2.1.

Table 2.1 Summary of regulations on spacers in various codes

Standard	Classification	General requirements
[UK] BS7973	Spacers are classified into four categories in accordance with their applications: Light (L) - supporting rebar not greater than 16 mm; Normal (N) - supporting rebar not greater than 20 mm; Heavy (H) - supporting rebar greater than 20 mm; Chairs (C) - supporting top reinforcement in slabs.	<u>Strength</u>: Spacers must be able to support reinforcement and additional loading during concreting; The mix used for cementitious spacers shall have a cube strength of at least 50 N/mm² at 28 d; Spacers should pass the load bearing capacity test. <u>Dimensional tolerance</u>: ±1 mm for covers/heights no more than 75 mm; ±2 mm for covers/heights larger than 75 mm. <u>Stability and fixity</u>: Spacers and chairs should pass the relative tests. <u>Durability</u>: Material of manufacture shall have equivalent durability to the concrete. The spacer or chair should not cause any deterioration to the reinforcement or the concrete.

Table 2.1 Summary of regulations on spacers in various codes (Continued)

Standard	Classification	General requirements
[UK] BS EN 13670	-	<u>Strength</u>: Spacers and chairs should be capable to carry the load during placing reinforcement and casting concrete. Concrete and cementitious spacers should have at least the same strength as the concrete in the structure. <u>Durability</u>: Concrete and cementitious spacers should give at least the same corrosion protection as the concrete in the structure. Chairs and spacers should not lead to enclosure of air, crack formation, penetration of water or damage the reinforcement. Long continuous chairs are generally not suitable in a corrosive environment. <u>Others</u>: Steel spacers in direct contact with the concrete surface are only permitted in a dry environment i.e. exposure class X0 and XC1 of EN 206-1.
[Australia & New Zealand] AS/NZS 2425	Strength grade based on the minimum test load capacity (kg): 60; 120; 200; >300 (Bar chair of strength grade > 300 kg are typically manufactures from a fine aggregate concrete.)	<u>Strength</u>: Spacers shall comply with the requirements of strength grade 60. The concrete in the chairs shall be greater than or equal to the strength of the surrounding concrete. Concrete bar chairs shall have a minimum concrete compressive strength of 60MPa. <u>Dimensional tolerance</u>: Height of bar chairs before loading < 75 mm: ± 1 mm generally, and $-1 \sim +2$ mm for concrete chairs; Height of bar chairs before loading ≥ 75 mm: ± 2 mm. <u>Stability</u>: Deflection under load $\leq \pm 3$ mm; After removal of load, the final recovered position < 2 mm, and for concrete chairs, no cracking shall be evident. For continuous bar chairs with height > 90 mm, any cumulative effect of deflection from being on already supported reinforcement should be taken into account. <u>Durability</u>: Concrete in the chair shall have equal or exceeding durability specifications of the surrounding concrete. Concrete bar chair should have a maximum rapid chloride permeability appropriate to the chloride permeability class set out. <u>Others</u>: Plastic chairs shall be designed to allow a nominal 20 mm aggregate concrete to penetrate the chair opening.

Table 2.1 Summary of regulations on spacers in various codes (Continued)

Standard	Classification	General requirements
[Germany] DBV Data sheet “Spacer” & DIN 1045- 1:2001	Classification according to their capacity: L1 - No increased demands on capacity and tilt stability; L2 - Increased demand on the carrying capacity and rollover stability. Types based on their shapes and dimensions: Wheel shape; Point shape(attached and unattached); Line shape(attached and unattached); Flat shape (attached and unattached). Selection of spacers could follow the recommendations in DIN 1045-1 based on the exposure classes with consideration of increased temperature stresses and resistance to freeze-thaw, water, chemical attack and chlorides.	<u>Strength, stability and fixity</u>: Spacers should have a sufficient capacity and tipping stability to fit the load and temperature demands; They should be safely attached to the reinforcing bar, and should have a low spring back effect. <u>Dimensional tolerance</u>: No more than 5mm. <u>Durability</u>: Material of manufacture should not corrode, promote the corrosion of reinforcement or damage the concrete; Spacers should be sufficiently resistant to the alkalinity of the concrete. <u>Others</u>: No particular requirements for the spacer material in terms of fire protection. Line spacers should be placed staggered to minimise the risk of crack formation.
[USA] ACI 315-99 & CRSI	Types of bar supports: Wire bar supports; Precast concrete bar supports; All-plastic bar supports. Classification of wire bar supports: Class 1 - Plastic-coated wire bar supports (maximum protection, intended for use in moderate to severe exposure applications); Class 2 - Stainless steel protected bar supports (moderate protection, intended for use in moderate exposure applications); Class 3 - Bright basic wire bar supports (no protection, intended for use where surface blemishes can be tolerated or where the supports have no contact with exposed concrete surfaces). All-plastic and precast concrete bar supports can be used for all corrosion resistance classifications.	<u>Strength</u>: Bar supports should be sufficient in number and strength to carry properly the reinforcing steel they support. <u>Dimensional tolerance</u>: Provide the required cover of no more than ± 3 mm. <u>Fixity</u>: Reinforcing steel must be accurately located in the forms and firmly held in place before and during the placing of the concrete. <u>Others</u>: Selection of the type of spacer is the responsibility of the contractor. Bar supports cast on ground should have and average spacing not exceeding 4 ft (1200 mm) in each direction. When used to support epoxy-coated reinforcement, spacers should be coated with dielectric (non-conducting) material, and wires or dowels should be epoxy-coated or plastic-coated.

Table 2.1 Summary of regulations on spacers in various codes (Continued)

Standard	Classification	General requirements
[Canada] CSA A23.1-14	Based on the material of spacers manufacture, spacers could be classified as: Plastic spacers, plastic coated steel spacers and prefabricated concrete spacers.	<u>Strength and stability</u>: Spacers should be with compressive strength equal to or exceeding the placed concrete, and should have sufficient strength and stiffness to carry the loads from reinforcement, construction crew and concrete pressure without failure, displacement or significant deformation. <u>Durability</u>: Bar supports should be non-conductive and have a geometry and bond characteristics that deter the movement of moisture from the surface to the reinforcement. <u>Others</u>: Slab reinforcement should be supported at maximum 4 ft (1200 mm) on each direction. Side form spacers supporting wall reinforcement should be placed with a minimum spacing of 8 ft (2400 mm) vertically and 4 ft (1200 mm) horizontally. Column spirals should have vertical spacers at each turn.
[China] JTG/T F50-2011	-	<u>Strength</u>: Spacers shall have sufficient capacity to carry reinforcement and other loads during construction. <u>Dimensional tolerance</u>: Thickness and height of spacers should not have negative error while the maximum positive error should not exceed 1mm. Spacers should be specially designed when used in crucial and anti-corrosion projects. <u>Fixity</u>: Spacers should be fixed stably with the reinforcement. The tying wire should not be encroached into concrete cover. <u>Durability</u>: Concrete spacers should have sufficient durability, and spacers made of other materials should not have adverse impacts on the surrounding concrete. <u>Others</u>: Spacers should be placed staggered between reinforcement and formwork. Spacers supporting bottom and side reinforcement should be used at least 3/m², and more spacers should be used at critical places.

2.1.2 Fixing and application

Fixing requirements include tying and spacing are of vital importance to achieve and maintain concrete cover in reinforced concrete members. Most standards specify spacers to be placed staggered with a minimum requirement in quantity. However, arrangement of spacers is still the responsibility of the contractor in most nations. Only a few standards include specific regulations on the tying and layout of spacers in different elements. Part 2 of BS 7973 provides one of the most detailed guidance on tying and spacing of spacers. A brief summary is listed below.

Slab

Spacers used to support bottom bar reinforcement in slabs shall be placed staggered at centres neither exceeding $50d$ (d represents the diameter of the reinforcement being supported) nor 1000 mm. Top reinforcement are always supported by chairs. Continuous chairs could be used in both doubly reinforced slabs and cantilever slabs, while individual chairs are only used in cantilever slabs fitted with protective tips. In all cases, chairs shall be positioned at centres not exceeding $50d$. When supporting welded fabric, spacers, individual and continuous chairs shall be located at centres not exceeding 500 mm despite the fabric are on the top or bottom face. In addition, circular chairs could also be used to support top fabric off a bottom layer following the restrictions of their diameters, lapping distances and tying times.

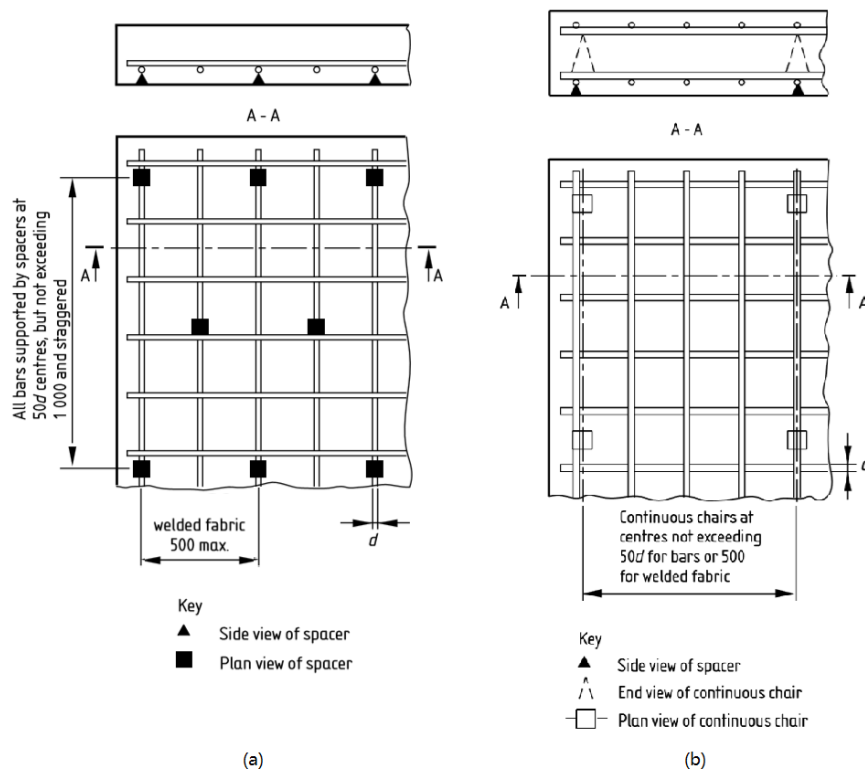


Figure 2.2 Spacers and chairs for: (a) bottom reinforcement; (b) top reinforcement in slabs (Unit: mm) (BS 7973-2:2001)

Beam

Spacers shall be attached on three faces of the same link, including end, bottom and side faces. Each end of a bar exposed to concrete cover shall be fixed with spacers as shown in Figure 2.3a. Spacers along the beams shall be placed at centres not exceeding 1000 mm. The placement of spacers on the bottom face alongside the width of the beams is dependent on the width of the beams as shown in Figure 2.3b. For beams less than 250 mm wide, one spacer shall be located in the middle of the bottom leg of the link. For beams larger than 250 mm wide, two spacers shall be positioned within 50 mm of the ends of the straight portion of the link bottom. Extra spacers are required to be used to maintain the spacing not exceeding 50 d (d represents link diameter) for beams wider than 500 mm. Spacers shall be positioned at the middle-height on each side of the beam as shown in Figure 2.3b. Extra spacers shall be used for deep beams with the depth greater than 100 d. They shall be positioned at the same level above the soffit on each side face with a distance not exceeding 50d, as shown in Figure 2.3c.

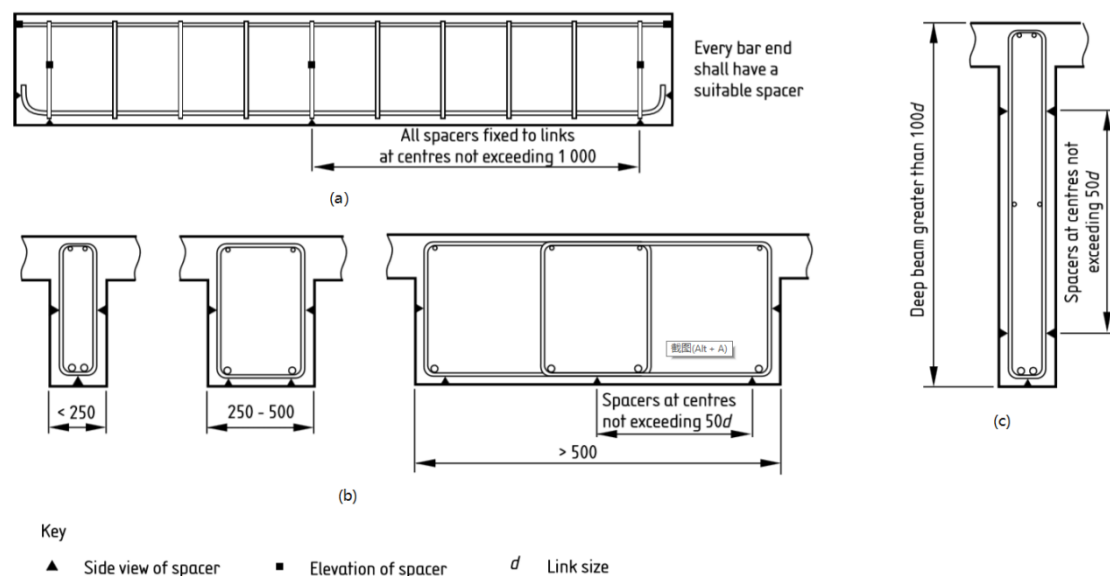


Figure 2.3 Spacers used in beams: (a) elevation; (b) cross-section; (c) cross-section of deep beam (Unit: mm) (BS 7973-2:2001)

Column

Along the side of columns, spacers attached to links shall be at the top, middle and bottom of each lift of concrete with the distance not exceeding $100 D$ (D represents diameter of main bar) as shown in Figure 2.4a. On the cross section of the column, spacers shall be placed on all sides of the same link within the distance of $50 d$ (d represents link diameter). For square or rectangular columns, spacer shall be positioned in the middle of the link when only one spacer is used on that side. Spacers used on the edge of each side shall be attached within 50 mm of the ends of the straight portion of the link. Additional spacer shall be positioned adjacent to the inner leg of one of the links when multiple links are used. Multifaceted columns and circular columns have same regulations of spacer position as square and rectangular columns. Spacer position requirements of all types of columns are shown in Figure 2.4.

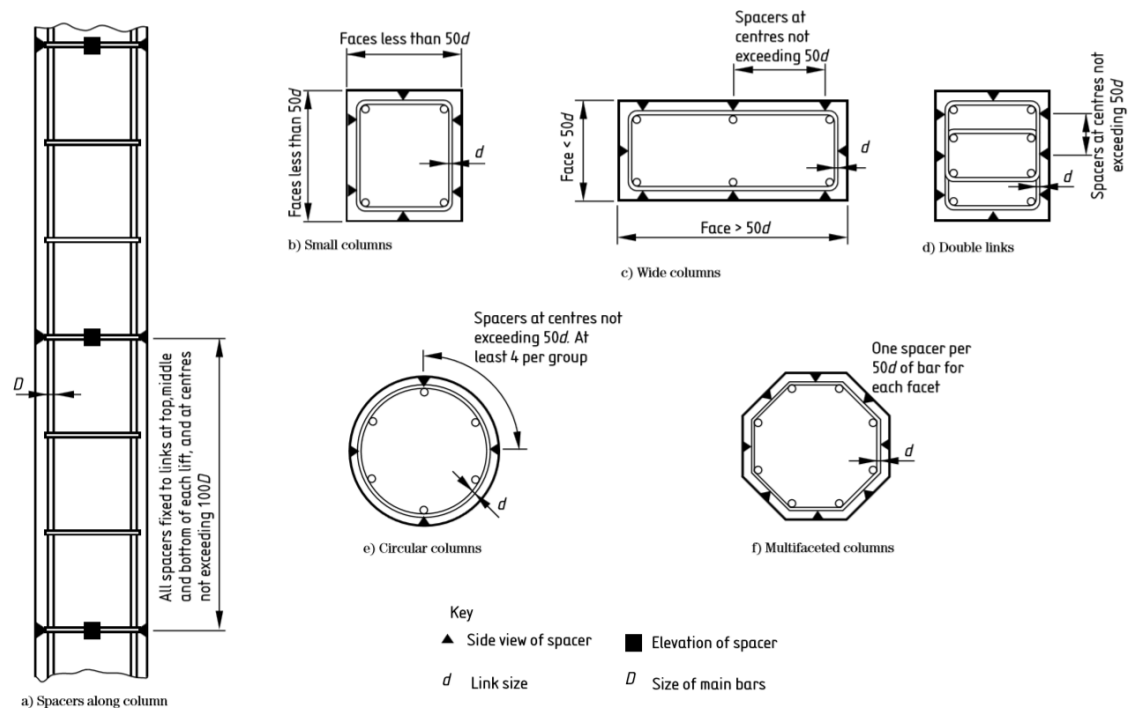


Figure 2.4 Spacers used in columns (Unit: mm) (BS 7973-2:2001)

Foundation and wall

Spacers used in foundations including reinforced strip footing, individual bases, ground beams, ground slabs and pile caps shall follow the same as for suspended slabs and beams. For walls, spacers supporting bars and fabric nearest to the face shall be placed staggered at centres not exceeding the greater of $50d$ (d represents the diameter of the supported reinforcement) and 500 mm. In walls up to 400 mm thick, bars and fabric on the opposing faces shall be separated by continuous chairs at centres not exceeding 1000 mm.

2.1.3 Commercially available spacers

Commercially available spacers are used in in-situ and precast constructions. There are numerous manufacturers worldwide providing spacers and chairs of various types. The selection of spacers and manufacturers is the responsibility of the contractor in most cases (Concrete Society, 1989). Although some guidance on spacer selection based on reinforcement size is included in certain standards, they are limited to broad suggestions on material type and their general capacity. Selection of specific spacer type remains to be multivariate.

The materials used and shapes of spacers are highly dependent on their suppliers. Although spacers are mainly produced either from plastic, cementitious materials or steel (Alzyoud et al., 2016), each contains many variations. For instance, a range of synthetic and semi-synthetic organic polymers could be used to produce plastic spacers, and cementitious spacers have a diverse composition made of various ingredients and mix proportions. In addition, spacers are produced by various methods and come in various shapes. For example, individual spacers can be moulded directly or through sectioning a whole-piece liner; the surfaces of the spacers may or may not be ground, blasted or coated (mainly for chairs). Therefore, the performance of spacers and chairs from different manufactures may vary widely.

According to a preliminary survey on the commercial spacers conducted in this PhD study (details shown in Appendix I), very few spacer manufacturers provide information related to the performance of their products. This is partially due to the lack of national regulations and partially due to general lack of appreciation on the quality of spacers in the industry. Among the information provided by suppliers, dimensions and strength are most commonly included. The expected cover depth a spacer could maintain is often referred as the only indicator of its dimension, while the strength of a spacer is normally provided in the form of a vague description such as a statement that ‘the strength of the spacers is not less than that of the surrounding concrete’. Fewer suppliers offer technical data sheets or test approvals on their products, and properties related to durability are either omitted or limited to chloride permeability and diffusivity of some cementitious spacers. However, degradation of a spacer could be caused by many factors. Cementitious spacers embedded with wires or plastic clips may have different resistance to aggressive ions from pure cementitious spacers, even when they are of the same composition. In addition, very few technical reports and quality assurance are provided by spacer manufacturers. Most of the available reports are classified according to material type without identifying their dimensions. Therefore, although various spacers and chairs are manufactured for all kinds of applications, the quality of these products are unknown and unregulated.

2.2 Effect of spacers on the properties of concrete

As mentioned previously, spacers are placed at certain distances and left permanent in concrete members. They interrupt the continuity of the concrete cover and replace a portion of concrete either in the cover zone or at the interlayer between reinforcement meshes. Previous studies of

their impacts on the properties of concrete, in particular durability and microstructure, are reviewed in this section.

Early investigations on the effect of spacers are mainly according to site observations of existing structures. For example, several field inspections have reported that reinforcement corrosion tended to occur at the locations of spacers (Kenai & Bahar, 2003; Poulsen, 2006; Shaw). Location of plastic spacers was reported to provide a preferential pathway for de-icing salts to penetrate into columns of road bridges (Poulsen, 2006). Similar inspection was also reported by Rostam (2005), which indicated the pathway alongside plastic spacer-concrete interface was due to the different thermal expansion of plastic and concrete. Severe reinforcement corrosion at the location of mortar spacers was observed in the inlet culverts of Barseback nuclear power plant (Shaw et al., 2003) and in the Algiers airport building (Kenai & Bahar, 2003). The porous microstructure of cementitious spacer was proposed as the main concern attributing to corrosion, especially when the spacers are of inferior quality with high open porosity.

Limited investigations were conducted on the influence of spacers. Levitt and Herbert (1970) investigated the corrosion of concrete beams containing mortar spacers and plastic spacers after weathering for ten years. Considerable corrosion was observed at the location of mortar spacers due to the poor quality of the spacers and the spacer-concrete interface. Spalling of concrete cover was observed at the location of A-shaped plastic spacers after several months' exposure, while the reinforcement at the location of circular plastic spacers only rusted slightly. This was attributed to the lack of openings in A-shaped spacers. In contrast, circular spacers contain large open spaces allowing concrete to nestle inside, and thus promoted spacer-concrete adhesion and compensation for differences in thermal deformation. However, it should be noted that this investigation is very old, and currently, at least 25% voids shall be included within the enclosed perimeter of plastic spacers according to BS 7973 (BS 7973-1:2001, 2001).

Tang and Utgenannt (2009) investigated chloride-induced corrosion of reinforced concrete slabs exposed to natural marine environment at a Swedish harbour for over 13 years. The slabs were cast during the winter 1991/1992 with concrete cover depths of 10, 15 and 20 mm. Three types of steel bars were investigated, and they were supported with mortar spacers on their ends. However, no further details relating to the spacers were provided. Concrete with different binders, w/b ratios and air contents were used. Highest corrosion rate was found at or near the spacer-concrete interfaces in half of the samples (including 35 significant cases and 3 moderate

cases), as shown in Figure 2.5. The interfaces initiated early corrosion and promoted chloride penetration. It was suggested that this was due to the poor quality of the interfaces. However, no supporting evidence was provided and this was not verified through further investigation.

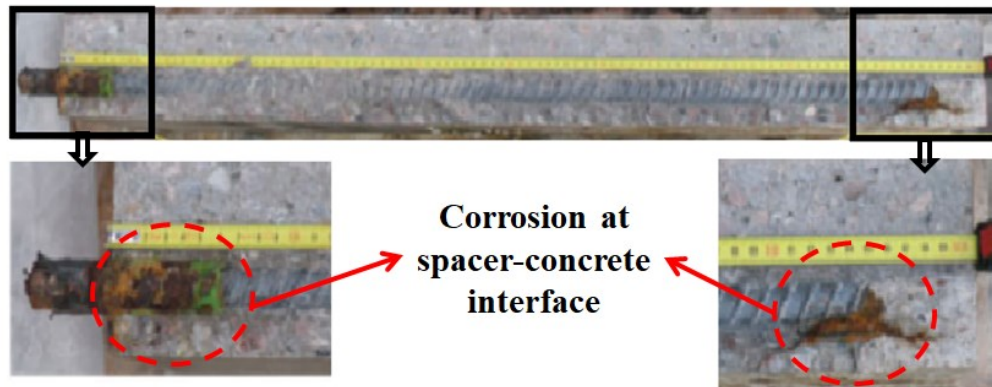


Figure 2.5 Corrosion at the interface between mortar spacer and concrete (Tang & Utgenannt, 2009)

Strømme (2017) also investigated the chloride penetration and reinforcement corrosion of concrete columns exposed to tidal zone for 30 years. Plastic spacers were used for maintaining correct placement of reinforcement. Concrete cover depths of samples with spacers were either 51 mm or 55 mm according to the measurement. Normal density concrete and two types of lightweight aggregate concrete (Lytag and Liapor) were used for sample casting. All columns were dynamically loaded to simulate wave action during the first 10 years and kept in water until being tested in 2016. An accumulation of chloride in concrete cover was observed in samples with spacers. An increased chloride content and penetration depths were found along the edges of spacers through μ XRF scan. It was also found that the effect caused by spacer is more obvious in lightweight concrete than in normal density concrete. However, the author stated that further research was required due to the limited sample quantity and errors caused by sample preparation.

Alzyoud et al. (2016) investigated the effect of spacers on concrete durability in respect of their mass transport (including permeability, diffusivity, absorption and chloride penetration) and microstructure. Cylindrical concrete samples with centrally placed spacers were casted. Typical individual spacers made of plastic, cementitious and steel were requested from leading manufacturers in the UK and used in this study. The cover depth was either 25 or 50 mm. CEM

I was used for all mixes with a water/cement ratio of 0.4. The samples were cured for 3 or 28d and conditioned at 20°C/75% RH, 20°C/55% RH or 50°C oven respectively prior to test. Increased mass transport was found by the incorporation of spacers despite their type. This was attributed to the poor spacer-concrete interface with higher porosity and lower cement content as shown in Figure 2.6. Samples with plastic spacers showed largest increase in mass transport and highest porosity at spacer-concrete interface, followed by those containing cementitious spacers and then steel wires. It was speculated that this is a result of the weak bond between plastic and concrete and the mismatch of their drying shrinkage and thermal expansion. Fine microcracks of ~ 4 to $6\ \mu\text{m}$ width were also detected on the exposed face, along the plastic and cementitious spacer-concrete interface. Based on these results, it was pointed that the spacer-concrete interface provided a preferential pathway for external media to penetrate into concrete structures, and the overall effect on concrete durability was significant due to their intensive usage in constructions.

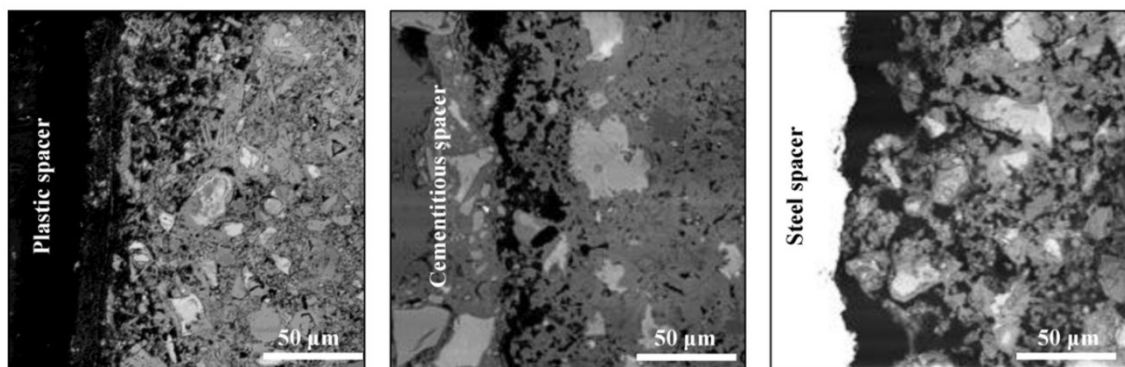


Figure 2.6 Backscattered electron images of spacer-concrete interface (Alzyoud et al, 2016)

Muslim (2021b) also investigated the effect of spacers on transport properties and microstructure of concrete containing supplementary cementitious materials (SCMs), namely silica fume, fly ash and ground granulated blast-furnace slag. Tests were carried out on cylindrical samples with plastic or cementitious spacers placed centrally. Samples were cured for 3, 28 or 120 days and conditioned at either 21°C/75% RH or 50°C oven. It was found that the inclusion of spacers increased mass transport despite the use of SCMs in concrete. A highly porous transition zone (with de-bonding microcracks at some locations) approximately 15 to 50 μm wide from the spacer boundary was observed through backscattered electron image analysis. Samples containing ground granulated blast-furnace slag showed the least negative

effect on concrete transport properties by spacers. In addition, the potential improvement on spacers through surface textures was studied (Muslim et al., 2021a). Composite cylindrical samples were cast in two stages, with the first half representing spacers and the second half representing the surrounding concrete. Eight types of spacer surface textures (shown in Figure 2.7) with different shapes and geometries were investigated. Tensile splitting and mass transport tests were carried out after curing for 1, 7 and 28 days. It was found that the inclusion of surface textures on spacers improved their interlock with concrete, leading to higher bond strength and lower permeability. However, not all surface textures were effective due to the presence of entrapped air voids at spacer-concrete interfaces.

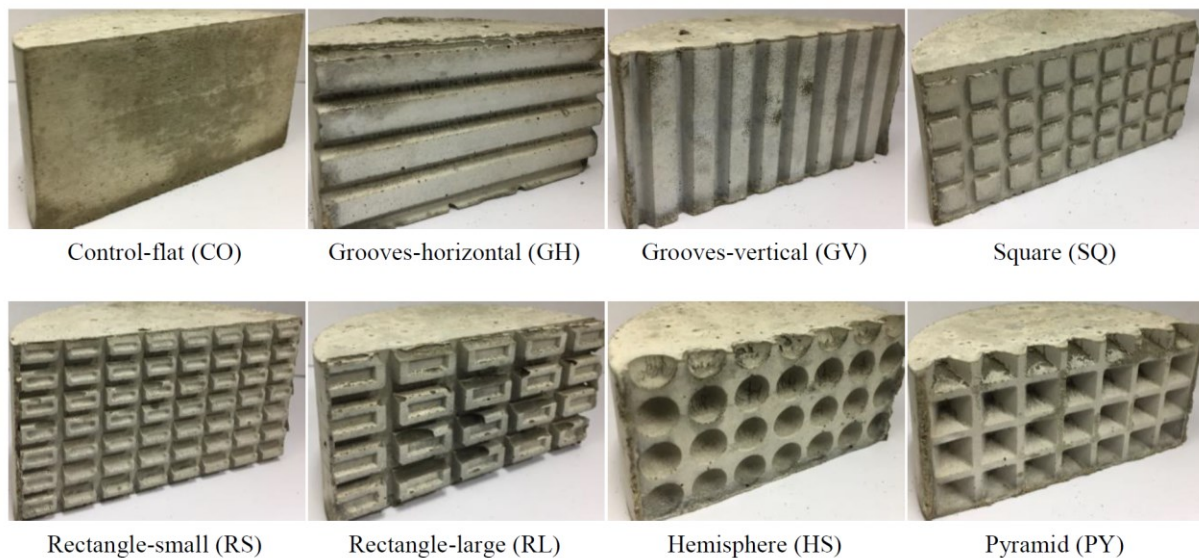


Figure 2.7 Surface textures of spacers (Muslim et al., 2021a)

Alzyoud et al. (2016) and Muslim et al. (2021b) observed the development of microcracks alongside the spacer-concrete interface, particularly when using plastic and cementitious spacers, which was one of the main reasons causing the increased mass transport properties of concrete. These microcracks could be generated by differential volumetric changes (drying shrinkage or thermal expansion) between the spacers and concrete. According to the Concrete Society Technical Report TR44 (2015), such non-structural cracks have widths and depths that change with time due to temperature and/or humidity variations, and therefore are unlikely to self-heal. Additionally, the cracked/debonded interface between spacer and concrete spans the entire concrete cover and directly exposes the reinforcement to aggressive species (Alzyoud et

al., 2016), which accelerates reinforcement corrosion. Furthermore, previous investigations were conducted under no external loading condition. Microcracks developed at the spacer-concrete interface are expected to propagate and widen when concrete structures are subjected to bending, shear, torsion or tension. Although crack control by limiting the maximum crack width is recommended for certain exposure classes in BS EN 1992-1-1:2004+A1:2014 (2014), it is not clear whether such requirements have included the effects of the spacer-concrete interface.

2.3 Concrete-to-concrete interfaces in structures

2.3.1 Introduction

Concrete-to-concrete interfaces are common in concrete constructions when placing fresh or hardened concrete against pre-existing hardened concrete. Placing hardened concrete against a hardened concrete substrate is common in prefabrications, precast and pre-stressed structures. This is widely used in the case of viaducts, bridge decks, detached houses, etc. Placing fresh concrete against a hardened concrete substrate is widely present in both new and existing structures. A typical fresh-to-hardened concrete interface is formed between concrete layers cast at different ages, such as the case of composite concrete structures when a new cast-in-place concrete layer is added to a precast member. Other examples include applying concrete overlays for finishing, rehabilitating and strengthening of existing concrete members (Aysha et al., 2014; Santos et al., 2012; Santos & Julio, 2011). The joining of two segmental concrete components is commonly achieved through pre-equipped metal joints or pre-stressed anchors. This section focuses on investigations relating to fresh-to-hardened concrete interfaces, which are more relevant to the case of spacer-to-concrete interface.

Performance of concrete structures with layers cast at different ages is highly dictated by the bonding at concrete-to-concrete interfaces. In both concrete repair and composite concrete construction, achieving long-term monolithic behaviour is to be expected. The requisites for achieving this are mainly sufficient bond compatibility and bond durability between the fresh and existing layers. Bond compatibility refers to the ability to withstand stresses induced by volume changes, chemical and electrochemical effects without deterioration, while bond durability refers to the maintenance of this bond with time (Morgan, 1996; Emmons & Vaysburd, 1994).

Bonding between different concrete layers is a complex mechanism influenced by a number of variables. Many researchers have indicated that the bond behaviour is largely dependent on the characteristics of the substrate, e.g. their compressive strength, humidity, temperature and surface morphology (Abu-Tair et al., 2000; Beushausen et al., 2017; Courard & Nelis, 2003; Garbacz et al., 2006; Hoła et al., 2015; Júlio et al., 2004; Santos et al., 2012). Some other factors were also suggested to be essential, including cohesion-related properties of the fresh layer such as strength capacity of the binder and mineralogical components (Emmons & Vaysburd, 1994), compaction and curing of the fresh layer (Santos & Julio, 2011; Xie et al., 2002), the use of bonding agent (Santos et al., 2012).

Bonding between concrete layers has been investigated through analysis on the interfacial microstructure. An interfacial transition zone (ITZ) with increased porosity is generally found between the substrate and the fresh layer. Formation of the ITZ is normally deemed as similar as the interfacial zone between aggregate and cement paste matrix, which is attribute to the “wall effect” that disrupts particle packing at the region close to substrate (Courard et al., 2014; Pigeon et al., 1992). On the contrary, Bissonnette et al. (2018) found a discontinuous interphase formed gradually with curing of the overlay, with a microstructure that is highly dependent on the substrate surface treatment. Xie et al. (2002) proposed a similar three-layered model of the ITZ as shown in Figure 2.8. The near-to-surface layers of the substrate and overlay were described as weakly-affected layers consisting of C-S-H, while a strongly-affected layer lies in between, predominantly composed of Ca(OH)_2 and needle-shaped Aft crystals. The weakly-affected layers were proposed to have little effect on the bonding behaviour. The penetration of fresh concrete at the near-to-surface layers may produce a tighter structure and therefore improve bonding. Various factors influence the thickness of the ITZ. Courard et al. (2014) proposed that an ITZ of about 100-150 μm thick is generally formed near the substrate. Kreiiger (1984) suggested that the thickness of ITZ is equal to the half of maximum grain size of the aggregate contained in the substrate, while Pigeon et al. (1992) stated that the thickness is dependent on surface treatment method of the substrate.

Research on understanding the influencing factors and the mechanisms that contribute to bonding behaviour between concrete layers are on-going. A particular challenge is to develop optimal methods for achieving sufficient and durable bonding between concrete layers. In the subsequent sections, a summary of investigations relating to the property of concrete-to-concrete interface, particularly interface between fresh and old concrete layers, is presented.

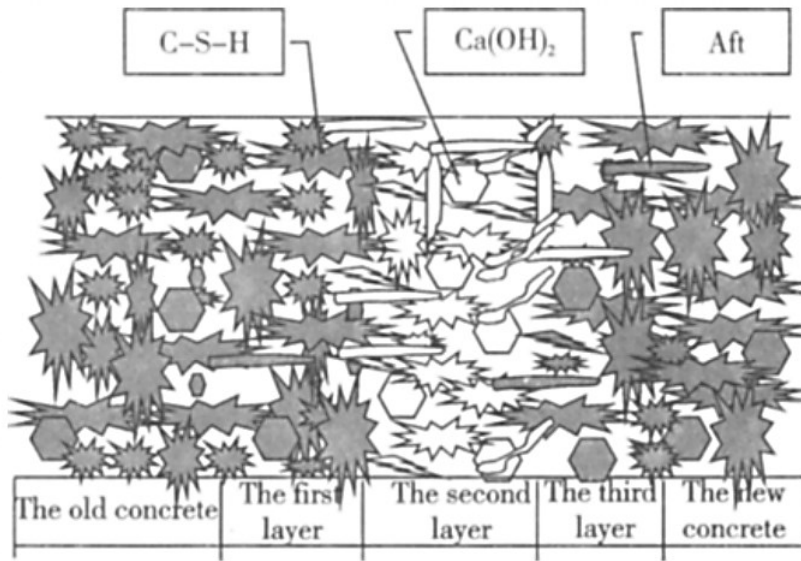


Figure 2.8 Model of ITZ proposed by Xie et al. (2002)

2.3.2 Bonding mechanism

Bonding, also referred as “adhesion”, can be discussed from two perspectives: the mechanisms of joining two materials at the boundary and the quantitative measurements of its strength. The understanding of bonding mechanism between fresh and old concrete is usually combined with investigations on conditions and kinetics of adhesion, while quantitative measurements of bonding intensity are normally expressed in terms of stress or energy required to separate the two layers (Bissonnette et al., 2011).

Adhesion mechanisms are generally categorized into mechanical adhesion and specific adhesion (Courard et al., 2014). Mechanical adhesion relies mainly on the anchorage resulting from hardening of the overlay inside open cavities of the substrate (He et al., 2017; Rashid et al., 2020). This is primarily driven by absorption of cement paste into the substrate, and therefore is highly dependent on the moisture condition and size of the cavities in the substrate (Courard, 2000). Specific adhesion includes thermodynamic interactions, physico-chemical adhesion and chemical bonding. Wetting of the solid substrate occurs when fresh concrete is cast against old concrete. On wetting, the surface energies of the solid and the liquid interact with each other, and a change in energy conditions occurs when a new interface is created

(Courard, 2002). When the total surface energy of the liquid/vapour and solid/vapour interfaces is larger than that of the freshly-formed liquid/solid interface, thermodynamic adhesion is generated. From this perspective, the contact angle of the substrate plays an important role. The lower the contact angle, the better the fresh concrete spreads and thus the more effective the interactions (Courard, 2000).

Physico-chemical adhesion refers to secondary inter-molecular bonding forces. Typical physico-chemical attractive forces are the Van der Waals forces, and they are attributed to dispersion forces or polar forces. Dispersion forces arise from internal electron motions which are independent on dipole moments, and polar forces arise from the orientation of permanent electric dipoles and the induction effect of permanent dipoles on polarisable molecules (Kinloch, 1987). Hydrogen forces could also be seen as a special case of dipole interactions, of which the range of actions extends further than those of other secondary forces. Compared to physico-chemical interactions, chemical bonding is normally of higher level of energy due to the development of covalent or ionic bond. This usually occurs when bonding agents are applied at the interface.

2.3.3 Factors affecting the properties of concrete-to-concrete interface

Many factors have been proposed to be influential on the bonding between different concrete layers. These are categorised into factors that relate to the properties of the substrate, overlay, environment and humidity.

2.3.3.1 Factors related to the substrate

Development of bonding between concrete layers is highly dependent on the quality of the substrate, especially the properties related to surface roughness, pore structure and moisture condition.

Surface roughness

Surface roughness of the substrate promotes mechanical interlocking and thermodynamic adhesion depending on the scale of the roughness (Courard, 2000). Macroscopic roughness typically at mm scale may boost mechanical interlock between concrete layers. Common surface preparation methods to obtain macroscopic roughness include surface texturing, mechanical roughening and blast methods. Surface texturing refers to the direct casting of

surfaces with rugged profiles, which is commonly used when casting concrete composites. Mechanical roughening such as jackhammering, drilling and scrubbing are more aggressive and tend to generate micro-cracks on the substrate. This could be detrimental for bonding especially when micro-cracks parallel to the surface are formed (Bissonnette et al., 2018). Blast methods are usually achieved through abrasives, pressurised water jet or a combination. These are used either directly or after mechanical roughening to remove the damaged concrete (Carter et al., 2002). It should be noted that mechanical roughening and blast techniques are also widely adopted for removing deteriorated concrete while generating roughness simultaneously. Increasing microscopic roughness of the substrate is more advantageous from the perspective of thermodynamic adhesion modification. Micro-roughness has been found to be efficient in modifying the contact angle of the substrate, and therefore improving the spread and wetting of fresh concrete against the substrate (Kinloch, 1987; Talbot et al., 1995).

Quantification of surface roughness helps to differentiate and standardise surface preparation techniques. It also helps to explain their influence on bonding between concrete layers. Various parameters have been proposed for quantifying surface roughness. Some commonly used parameters of roughness and their calculations are listed in Table 2.2. These parameters can be determined by analysing 2D profiles of the sample surface.

Table 2.2 Parameters for surface roughness quantification

Parameter	Equation	Parameter	Equation
Average roughness (R_a)	$R_a \approx \frac{1}{n} \sum_{i=1}^n z_i $	Root-mean-square roughness (R_q)	$R_q \approx \sqrt{\frac{1}{n} \sum_{i=1}^n z_i^2}$
Mean peak height (R_{pm})	$R_{pm} = \frac{1}{5} \sum_{i=1}^5 p_i$	Mean valley depth (R_{vm})	$R_{vm} = \frac{1}{5} \sum_{i=1}^5 v_i$
Mean peak-to-valley height ($R_{z(DIN)}$)	$R_{z(DIN)} = \frac{1}{5} \sum_{i=1}^5 (p_i + v_i)$	Ten points height ($R_{z(ISO)}$)	$R_{z(ISO)} = \frac{1}{5} (\sum_{i=1}^5 p_i + \sum_{i=1}^5 v_i)$

Note: n is the number of discrete measurements; z_i is the amplitude of each measurement; p_i is maximum peak height in each sampling length; v_i is maximum valley depth in each sampling length.

The British Standard (BS EN 1504-10:2017, 2017) recommends three methods for characterising surface roughness: the surface texture profile method, sand area method and

saw-teeth profile method. The surface texture profile method relies on the use of a stylus instrument that moves along a predetermined horizontal path and records the vertical deflection as a function of position (BS EN ISO 4288:1998, 1998). The sand area method works by pouring 5 to 25 ml sand onto the surface, spreading the sand into a circular patch and measuring the diameter of the circle. Roughness is determined based on the ratio of sand volume to the square of mean diameter of the sand patch (BS EN 1766:2017, 2017). The saw-teeth profile method is specially recommended for water-jetted surfaces. A profilometer is used along a selected segment to measure the perpendicular distance between a straight line and the surface profile, which is then transferred into a roughness value (BS EN 1504-10:2017, 2017). It should be noted these methods are limited to substrates with horizontal surfaces and their accuracy is dependent on the operator. Apart from these methods, non-contact techniques have also been used such as the adoption of digital surface roughness meter (Maerz & Myers, 2001), microscopy (Garbacz et al., 2006b), ultrasonic (Santo et al., 2010; Czarnecki et al., 2006) and 3D laser scanning (Duarte et al., 2014).

Pore structure

Pore structure of the substrate affects penetration of fresh concrete and therefore the new-to-old concrete bond. Several parameters to characterise this property have been proposed, such as open and close porosity, relative impregnation ratio and water absorption (Courard, 2000). Capillary absorption is deemed more appropriate as it is the primary driving force for the overlay to ingress into substrate. However, capillary absorption is affected by many factors such as moisture content and distribution, and therefore it may be difficult to obtain an accurate value. Adopting capillary absorption as the only index may not be sufficient to fully understand the effects of substrate pore structure.

Mercury intrusion porosimetry is a popular method for analysing meso and macropores, particularly between 4 nm and 60 μm (Rouquerol et al., 1994). Connected porosity, specific surface and pore size distribution can be determined through this method (Zornoza-Indart & Lopez-Arce, 2019). These parameters are obtained by forcing mercury into pore spaces under high pressure. However, it is a destructive lab-based method and makes simplistic assumptions concerning the pore structure which mean that the pore sizes are under-estimated substantially due to the so-called ‘ink-bottle effect’. The use of microscopy can provide a more reliable analysis of pore geometry and sizes at the mesopore scale and above. Optical or electron microscopy can be used, depending on the required resolution. This method is non-destructive

and provides additional information such as pore connectivity, accessibility and tortuosity if the imaging is carried out in 3D. In addition, the spatial distribution of pore sizes such as at the near-to-surface zone can be analysed.

Moisture condition

The substrate moisture condition affects concrete-to-concrete bond as follows. A dry substrate pulls water from the fresh overlay before it hardens. Excessive loss of water to the substrate could lead to inadequate hydration of the fresh concrete, resulting in a poor overlay and weak interfacial bond. In contrast, substrate with high moisture content may dilute the interface, consequently increasing the water/binder ratio and drying shrinkage, and decreasing bond strength. In addition, filling of open pores with excess water inhibits the absorption of fresh cement paste into the substrate and therefore weakens the interlocking at the interface.

Many studies have been carried out to find the optimal substrate moisture condition at the time of applying fresh concrete. The saturated surface dry (SSD) condition is often recommended prior to applying fresh layer for concrete repair. However, this is proposed to avoid problems rather than to achieve the best bond (Courard et al., 2011). Different optimum moisture conditions have been indicated that correspond to different substrate and overlay materials. However, a thorough understanding of the actual mechanism is challenging due to difficulty in controlling and recording the moisture condition of the substrate. Furthermore, detecting and tracing water movement between substrate and overlay is difficult as it could be driven by various mechanisms such as gravity, hydration or temperature gradients.

2.3.3.2 Factors related to the fresh layer

Influence of the fresh layer on concrete-to-concrete bonding could be analysed from two aspects: initial stage of casting and later stage after hardening of the fresh layer. At the early stage, the interaction between the fresh and the existing concrete can be analysed as a liquid to solid interaction. This is mainly related to thermodynamic and kinetic processes (Courard, 2000). The thermodynamic process refers to the initial spreading of the fresh concrete and this is mainly dependent on the surface energy of the fresh concrete and substrate. The kinetic process refers to the further movement of the fresh concrete, and this includes penetration into substrate driven by capillary absorption. Two theories have been used to describe this process: capillary rise according to Jurin's law (Berthier et al., 2019) and the Washburn's law (Jiang, 2018), represented by Eq. 2.1 and Eq. 2.2 respectively. Jurin's law is more suitable for fine

capillaries while Washburn's law is more applicable for large capillaries. The penetration is also dependent on the fluid viscosity and surface tension.

$$H = \frac{2\gamma \cos \theta}{\rho g R} \quad \text{Eq. 2.1}$$

$$H^2 = \frac{R \cos \theta}{2\eta} \gamma t \quad \text{Eq. 2.2}$$

Where:

H = capillary rise (m)

γ = surface tension of the liquid (N/m)

θ = contact angle

ρ = density of the liquid (kg/m³)

g = local acceleration due to gravity (m/s²)

R = radius of the pore (m)

η = viscosity of the liquid (N/m²·s)

t = time (s)

Properties of the overlay following hardening also play an important role on the development of bond. Materials that generate excessive heat and shrinkage could lead to microcracking at the interface (Santos & Julio, 2011). Thermal coefficient of expansion, creep and elastic modulus of the overlay are generally expected to be the same as those of the substrate, yet this is often difficult to achieve. Differential deformation between overlay and substrate under temperature and mechanical action could result in dimensional instability that degrades the bond. In addition, some overlay materials contain bonding agents or chemical additives. The presence of these active ingredients makes the bond development even more complicated, and they should be analysed individually according to their specific composition.

2.3.3.3 Factors related to environment

It is well-known that the ambient temperature and humidity before and after the application of the fresh layer are important factors for achieving a good quality bond. The optimal curing regime varies with the composition of the overlay and substrate. The quality of workmanship is also important. This is especially critical during substrate preparation, fresh layer placement and fresh layer compaction. However, these factors are difficult to record and analyse quantitatively.

2.3.4 Bond strength test

Bond strength is a fundamental property of interfaces. De-bonding of the overlay from substrate can be caused by different external forces such as tensile, shear or a combination of these. However, mechanical bonding may perform differently depending on the stress conditions. For instance, surface roughness of the substrate may be beneficial for improving the shear bond strength, but have limited contribution to tensile bond strength. Therefore, various test methods have been proposed for evaluating bond strength based on different mechanisms. Table 2.3 provides a comparison of some typical test methods. Selection of the specific method is normally based on the dominant interface stress condition of the structure in actual application.

Table 2.3 Comparison of bond strength test methods

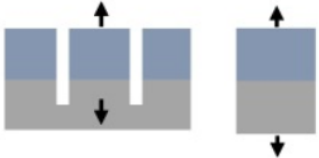
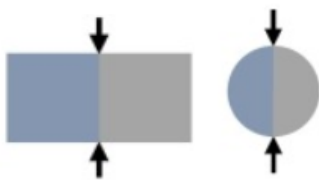
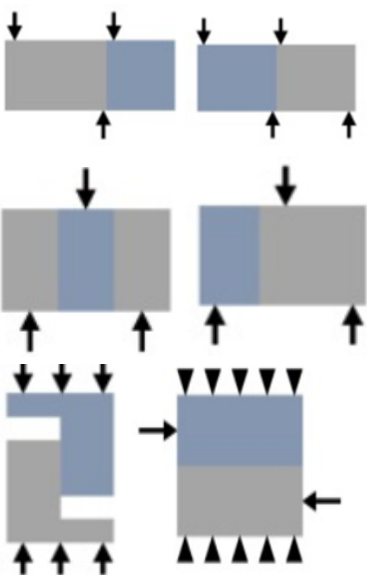
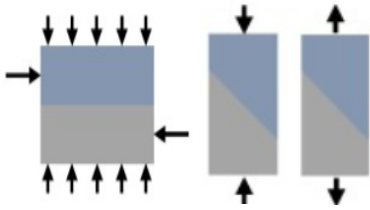
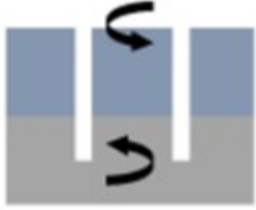
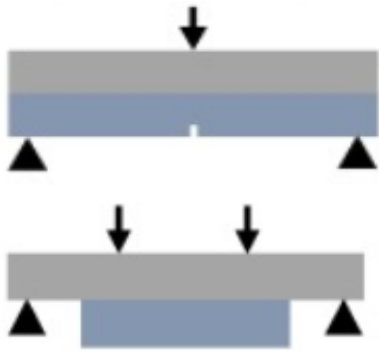
Test mode & failure stress (in brackets)	Typical loading scheme	Advantages	Disadvantages
Direct tension (Pure tension)		Applicable both in-situ and in the lab.	1) Sensitive to eccentricity. 2) Limited actual application condition.
Indirect tension (Pure tension)		Easy to prepare samples and conduct the test.	Prone to stress concentrations at the zone around loading points.
Shear (Pure shear)		Able to investigate pure shear resistance separately.	1) Can only be conducted in lab. 2) Difficult to avoid the effects of the undesirable bending moment induced by the loading scheme in tests (Chen et al., 1995).

Table 2.3 Comparison of bond strength test methods (Continued)

Test mode & failure stress (in brackets)	Typical loading scheme	Advantages	Disadvantages
Compression-shear or tensile-shear (Mixed mode)		Close to the stress conditions of most common types of actual constructions.	1) Slant test results are highly dependent on the angle of the interface and insensitive to surface preparation and surface roughness. 2) Incorporation of compressive stress can lead to overestimation of the influence of surface preparation. 3) Sensitive to differences in elastic modulus between the two materials, consequential local stress concentration could affect test results (Austin et al., 1999).
Torsion test (Pure shear)		Applicable both in-situ and in the lab.	Incompatibility of the critical failure plane with the interface since the critical failure plane under pure tension tends to be spiral shape with a 45° incline, which is different from the geometry of the interface.
Bending test (Mixed mode)		1) Capable of simulating the bond behaviour of repair or composite construction such as beams and slabs. 2) Provide information related to cracking behaviour (Teng et al., 2003).	1) Can only be conducted in the lab. 2) Require large samples and time-consuming tests.

Note: Images of loading schemes from López-Carreño et al. (2017)

2.3.5 Long-term performance testing of concrete-to-concrete interface

Research related to long-term performance of concrete-to-concrete interface has been conducted from the perspective of dimensional compatibility between substrate and overlay. These investigations have mainly focused on shrinkage and stiffness properties of the overlay (Decter, 1997; Mangat & Limbachiya, 1995) or the interfacial deformation under various loading conditions (Venkateela et al., 2017). However, limited studies have been conducted on mass transport properties of concrete-to-concrete interface.

Ding et al. (2019) investigated the permeability of interface between strain-hardening cementitious composite (SHCC) and normal concrete (NC). Semi-cylindrical samples were prepared with NC and cured, followed by casting of the second half with SHCC. Permeability of the composite was tested using a digital impermeability meter. Specimens were split along the bonding surface after the permeability test, and seepage height of the split surface was recorded and compared as a direct index reflecting the permeability of the interface.

Tayeh et al. (2012) investigated the permeability of the interface between ultra-high performance fibre concrete (UHPFC) and NC. Cylindrical samples composed of half-UHPFC and half-NC and NC-cylindrical samples with UHPFC-layer overlaid on top were prepared to simulate different site conditions. Rapid chloride permeability, gas permeability and water permeability tests were conducted. The rapid chloride permeability test was performed in accordance to ASTM C1202-97 (1994). Gas permeability and water permeability tests were conducted using the apparatus developed by Cabrera and Lynsdale (1988). Samples were placed and sealed in the permeability cell, then subjected to either a gas or water pressure at 2.5 bars. Results of the composite samples were compared with the control samples made of pure UHPFC or pure NC.

Long et al. (2014) investigated the permeability and ion diffusion of new-to-old concrete composites via the rapid chloride permeability test. These were performed on cylindrical samples with new layer overlaying on top of the old layer. Ueda et al. (2011) investigated the water permeability of repaired concrete. The lower faces of the degraded concrete were repaired by spraying with different materials and then exposed to outdoor conditions for 5 years before being cut into cubes for testing. A small hole was bored through the centre and filled with water to investigate leakage. A reagent that changes into red colour when in contact with water was sprayed onto the sides of the samples before starting the test. Critical position of water leakage was then indicated by the change in colour. Water absorption was also

investigated through a similar set up by injecting water into each hole and monitoring the water level over time.

In general, it can be said that there is a lack of test methods that assess long-term performance of concrete-to-concrete interface directly. This could mainly be attributed to the difficulty in isolating the interface from fresh and old layer. More investigations on the interfacial microstructure using advanced microscopic technique are required. These could provide a wide range of interfacial properties at the meso and micro scale. However, quantitative relationships between these properties and long-term performance of composite elements remain to be investigated.

2.4 Summary

The current state of reinforcement spacers and existing knowledge on their effects on concrete microstructure and durability were reviewed in this chapter. Many different types of spacers are available and are used in concrete construction. However, limited standards have clear regulations governing their performance and evaluation, especially in terms of durability. It is especially important that cementitious spacers are durable since they provide a direct route between external environment and embedded reinforcing steel. However, there is a lack of investigation on the performance of these spacers and their effects on the long-term durability of concrete.

Available research showed that the interface between spacers and concrete is highly porous and microcracked, which provides preferential pathways for aggressive agents (gasses, water and dissolved ions) to penetrate into concrete. However, little research has been conducted on improving the microstructure of the interface and its resistance against mass transport to enhance concrete durability. Therefore, a review on the concrete-to-concrete interface in concrete structures was carried out to summarise current understanding of the bonding mechanism between cementitious materials and provide inspirations for potential approaches to improve the spacer-concrete interface.

Chapter 3 Methodology

This chapter presents the main experimental approach and procedures used in this thesis. Details of the materials, sample preparation, instrumentation and test methods that are common to all results chapters are presented. Additional experimental approaches that are unique to Chapters 4 to 7 will be described in each corresponding result chapter.

3.1 Materials

The main binders used in this thesis are Portland cement CEM I 52.5N (used in Chapters 5 to 7) and ground granulated blast-furnace slag (GGBS) (used in Chapter 7). Their oxide compositions determined by XRF are listed in Table 3.1. Specific gravity of the cement and GGBS are 3.15 and 2.94 respectively. Thames Valley sand and gravel complying with the BS EN 12620:2002+A1:2008 (2008) grading were used as fine and coarse aggregates respectively. Their physical properties and particle size distributions are shown in Table 3.2 and Figure 3.1, respectively. MasterGlenium SKY 1901 and MasterEase 3925 were used as superplasticisers to improve workability. The required dosages of these admixtures were determined from trial mixes according to flow table and slump test results. The mix proportions of mortars and concretes used in each results chapter will be presented in the respective chapter.

Table 3.1 Oxide composition (% wt.) of binders used in this study

Binder	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	SO ₃
GGBS	41.5	34.7	11.5	0.5	6.1	0.7	0.2	2.9
CEM I	63.4	20.8	5.4	2.4	1.5	0.7	0.3	2.9

Table 3.2 Physical properties of aggregates

Aggregate	Maximum size (mm)	Specific gravity	24h water absorption (%)
Sand	5	2.53	0.5
Gravel	10	2.63	0.61

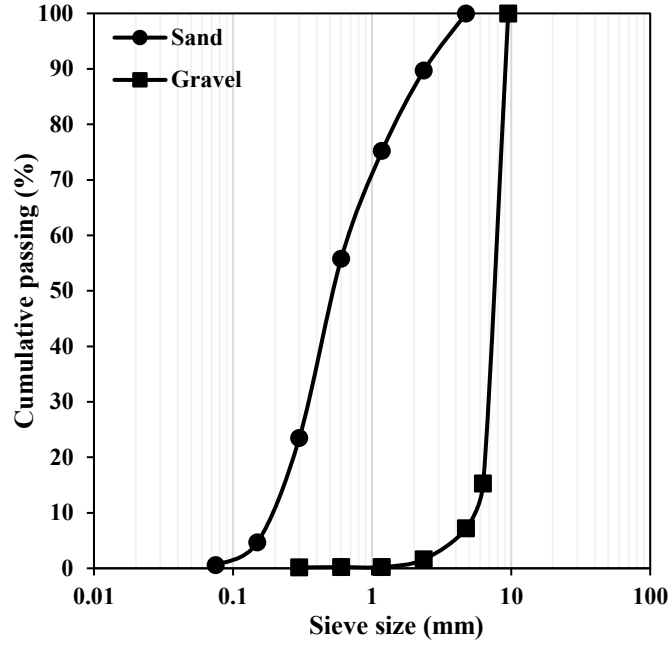


Figure 3.1 Particle size distribution of aggregates

3.2 Spacer production method

A method to manufacture spacers with rough surfaces and exposed unreacted cementitious particles and fibres simultaneously to enhance mechanical and chemical bonding, is proposed and developed in this thesis (used in Chapters 6 and 7). This method is based on casting the spacer with pre-fabricated grooves at designated positions, and then splitting the spacer at these locations to produce the desired surface. Trials have been carried out on cylindrical samples made with different types of grooves, then split to generate a freshly exposed surface to bond with concrete. The shape of the spacers was simplified into half-cylinder in this study to facilitate assessment of spacer-concrete bond strength, microstructure and mass transport properties. Materials and mix compositions for producing such spacers will be discussed in detail in Chapters 6 and 7. Spacers were casted in cylindrical steel moulds (with the diameter of 100mm and thickness of 50mm) in two equal layers, each followed by compaction using a vibrating table. The spacers were surrounded by wet hessian and covered with plastic sheeting for 24 hours, then demoulded by disassembling the mould and manually pushing the spacers out. The spacers were then cured in a fog room at 21°C, 100% RH for 7d before being split.

To produce the grooved samples, many trial experiments were carried out using strips of different shapes, materials and sizes as shown in Table 3.3. Plastic strips with triangular cross-section were chosen for further investigation because it is more rigid and practical for controlling the groove orientation. The results showed that right angled triangular cross-section strips of $4 \times 4 \text{ mm}^2$ was most optimal in controlling crack propagation and ensuring that splitting occurs at the required position. Several orientations of strips and loading directions were tested and compared in terms of the quality of the fractured surface as shown in Table 3.3. Steel rods slightly larger than the grooves were placed on the sample to ensure load distribution. The best splitting results were observed when grooves were applied on all four sides of the specimen and loading was applied longitudinally. The trial experiments also found that fibre-reinforced samples could be split cleanly across the grooves without generating additional visible damages as shown in Figure 3.2.

Table 3.3 Selection of strips to produce grooved samples and loading systems

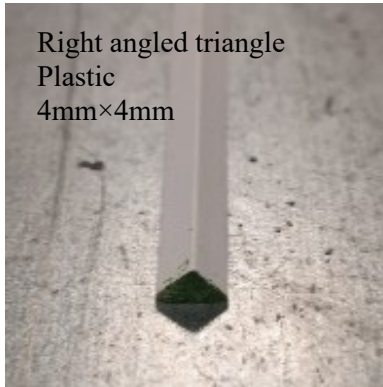
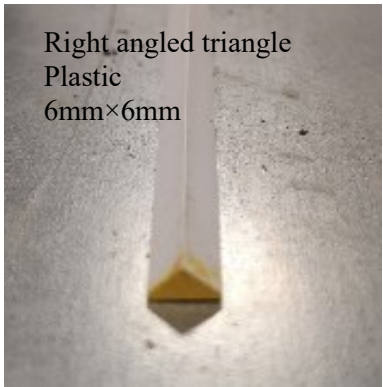
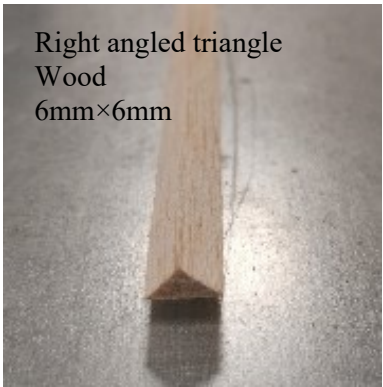
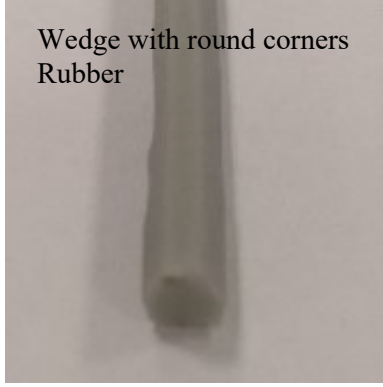
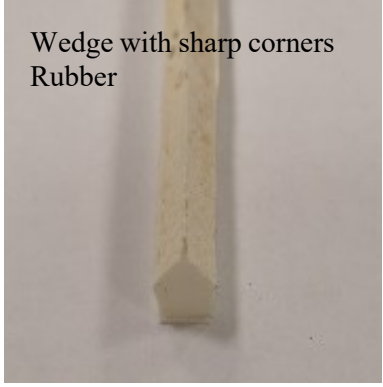
Types of strips		
 Right angled triangle Plastic 4mm×4mm	 Right angled triangle Plastic 6mm×6mm	 Right angled triangle Wood 6mm×6mm
 Wedge with round corners Rubber	 Wedge with sharp corners Rubber	

Table 3.3 Selection of strips to produce grooved samples and loading systems (Continued)

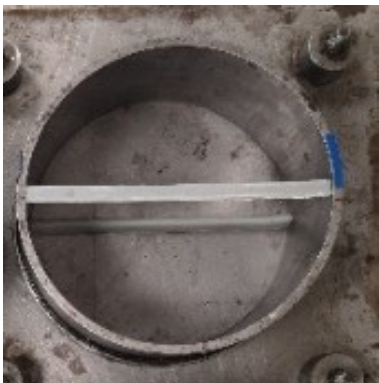
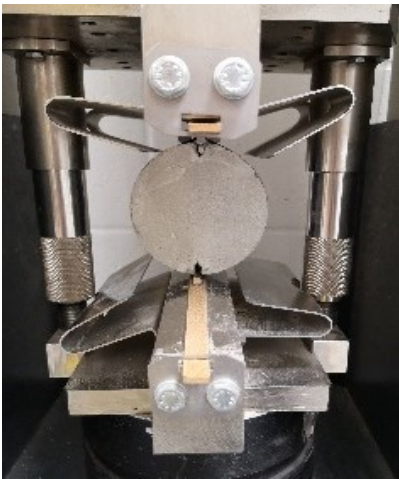
Orientation of strips		
		
a) 2 sides	b) Top & bottom	c) 4 sides around
Samples with different groove orientations		
		
a) 2 sides	b) Top & bottom	c) 4 sides around
Loading Apparatus		
		
a) Radially	b) Longitudinally	

Table 3.3 Selection of strips to produce grooved samples and loading systems (Continued)

Typical phenomenon after loading		
		
a) 2 sides-groove Radially loading	b) Top & bottom-grooved Longitudinally loading	c) 4 sides around-grooves Longitudinally loading



Figure 3.2 Fibre-reinforced mortar split using the optimal groove orientation and loading regime

3.3 Mechanical properties

3.3.1 Compressive strength

Compressive strength of the investigated spacers (Chapters 6 and 7) was tested according to BS EN 12390-3:2019 (2019) . Cubic samples of $50 \times 50 \times 50 \text{ mm}^3$ were loaded at a rate of 0.3 MPa/s until no greater load could be sustained. Average compressive strength and standard deviations was calculated according to the results of three or four replicates.

3.3.2 Modulus of rupture

This was measured according to ASTM C293-02 (2017) using the test apparatus shown in Figure 3.3. This was carried out to compare the modulus of rupture of different commercial cementitious spacers in Chapter 4. Mini beams of $5 \times 5 \times 24 \text{ mm}^3$ were extracted from commercial cementitious spacers using a precision diamond cutter and tested by applying a mid-point load at a deflection rate of 0.2 mm/min and the largest applied load was recorded automatically. The modulus of rupture was calculated according to the following equation

$$R = \frac{3FL}{2bd^2} \quad \text{Eq. 3.1}$$

Where:

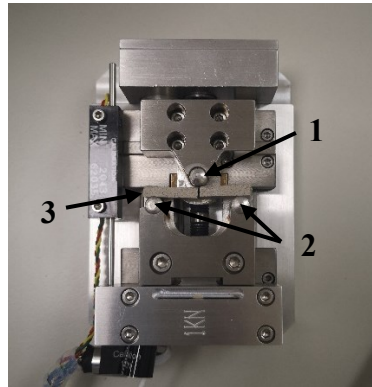
R = Modulus of rupture (MPa)

F = Maximum applied load (N)

L = Span length (mm)

b = Average width of sample (mm)

d = Average depth of sample (mm)



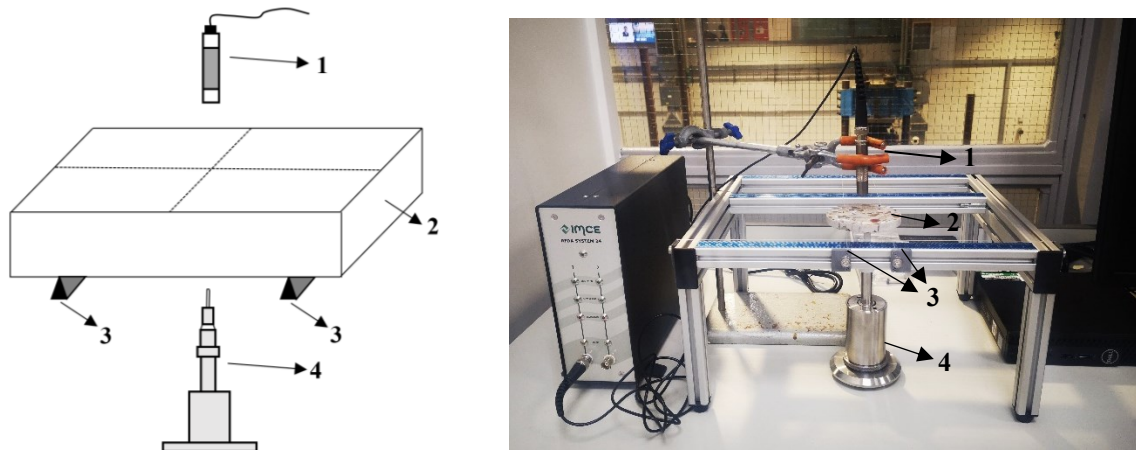
Notation: 1. Loading point; 2. Supports; 3. Sample

Figure 3.3 Modulus of rupture test

3.3.3 Dynamic Young's modulus

Young's modulus of various commercial cementitious spacers (Chapter 4) was measured using a non-destructive impulse excitation technique with an IMCE Resonant Frequency and

Damping Analyser (RFDA) in accordance with ASTM E1876-15 (2015). The test setup is shown in Figure 3.4. A prismatic sample with a cross section of $15 \times 30 \text{ mm}^2$ and span of 30 mm was simply supported on a test frame 0.224 L away from its edges, where L represents the span of sample. A small projectile was placed at the centre point and the sample was tapped from the underside. The induced vibration signal was collected by a sensitive microphone above the sample. The acquired vibration signal in the time domain was converted to the frequency domain by fast Fourier transformation. Subsequently the resonant frequency was determined to calculate Young's modulus based on classical beam theory, using the ICME RFDA professional software. Each reported result was based on the average of four measurements.



Notation: 1. Microphone; 2. Sample; 3. Supports; 4. Automatic tapping device

Figure 3.4 Impulse excitation technique for measuring dynamic Young's modulus

3.3.4 Bond strength

Bond strength between the spacer and concrete (Chapters 6 and 7) were tested through tensile splitting following the procedure described in BS EN 12390-6:2009 (2009). Test setup is shown in Figure 3.5. Cylindrical samples (diameter of 100 mm and thickness of 50 mm) with one half representing the spacer and the other half representing concrete were prepared. Thickness and diameter of the sample were measured at five different places before testing and averaged for calculation. The exact position of the spacer-concrete interface was marked and aligned with the loading direction. Plywood strips were placed between the sample and platen to reduce stress concentration at the loading point. Compressive load was applied on the spacer-

concrete interface at a rate of 0.03 MPa/s until the sample fully failed. Bond strength was calculated according to the following equation

$$f_{ts} = \frac{2F}{\pi T d} \quad \text{Eq. 3.2}$$

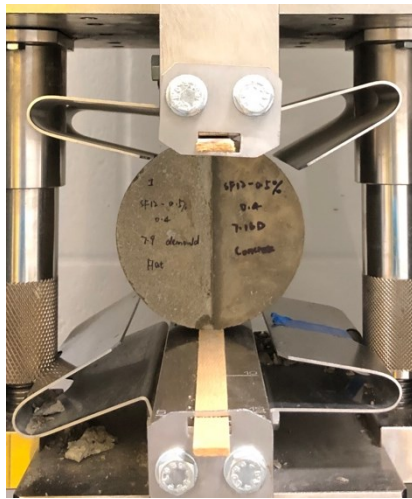
Where:

f_{ts} = Bond strength (MPa)

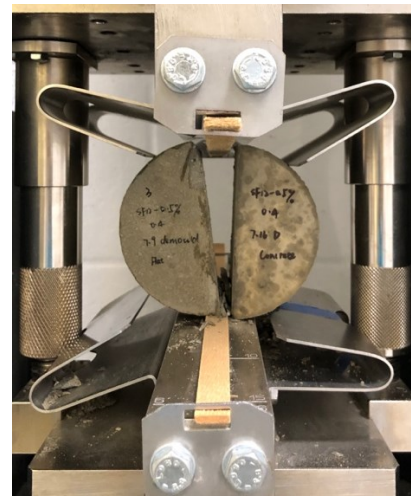
F = Maximum applied load (N)

T = Thickness of sample (mm)

d = Diameter of sample (mm)



a) Start of test



b) End of test

Figure 3.5 Setup for measuring bond strength via tensile splitting testing

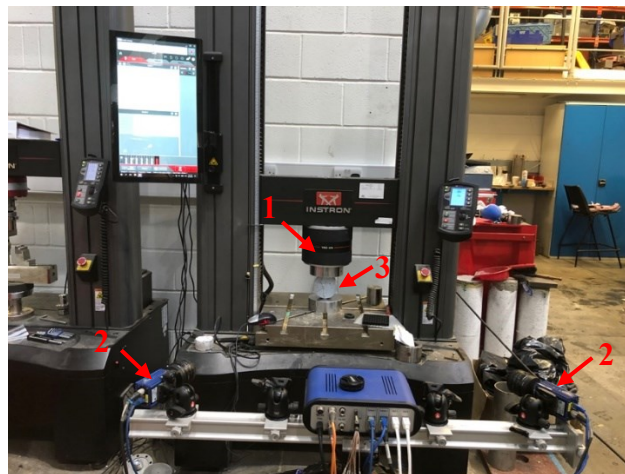
3.3.5 Digital image correlation (DIC)

Crack initiation and propagation on the surface of composite samples during bond strength testing was tracked and analysed through DIC. This method is particularly suited for samples containing fibre-reinforced spacers (Chapter 6), which showed improved ductility during testing. For accurate DIC analyses, the composite samples were painted white and sprayed with random black speckles prior to testing as shown in Figure 3.6. The setup for DIC is shown in Figure 3.7. Two digital cameras were used to capture the sample surface during the entire loading regime. A calibration plate was placed next to the samples prior to loading to position

the centroid of the samples and any movement was avoided after the calibration process. Image capture was then started followed by loading to ensure the camera achieves a stable focus on the surface of the samples. One image was captured every second based on the accuracy requirement of the test method. Post analysis was conducted through DaVis software, which provides data on deformation and displacement on any selected areas of the sample surface.



Figure 3.6 Speckled sample for DIC



Notation: 1. Loading machine; 2. Cameras; 3. Sample

Figure 3.7 Setup for DIC

3.4 Mass transport properties

Mass transport properties were tested in the sequence of oxygen diffusivity, oxygen permeability and water absorption in order to characterise the effects of spacers on concrete durability (Chapters 5 to 7). These properties were tested because concrete durability depends

largely on its ability to resist penetration of water and other aggressive species (such as chlorides, CO₂, oxygen and sulphates) through diffusion, permeation and capillary sorption (Wu et al., 2015). Tests were carried out on cylindrical samples with a diameter of 100 mm and thickness of 50 mm pre-conditioned to constant weight by drying in a 50°C oven. The procedure for each test follows the steps proposed by Wong et al. (2007) and Wu et al. (2014), and is described in the following sections.

3.4.1 Oxygen diffusivity

Gaseous diffusion refers to the gas movement driven by a concentration difference. The diffusion test was carried out by exposing the top and bottom flat surfaces of the cylindrical sample to a stream of oxygen and nitrogen gas at equal pressure respectively, and then measuring the oxygen concentration in the nitrogen stream. Setup for this test is shown in Figure 3.8.

Sample was first placed in the diffusion cell with silicone rubber surrounding its curved surface. The sample was then sealed by applying a 15 kN load on top of the cell lid, which was transferred to the silicone rubber to create lateral expansion. Subsequently, the oxygen and nitrogen flow were applied to the sample. Pressure difference between these two streams was measured with the left manometer shown in Figure 3.8, and this was adjusted to approximately 0. The oxygen concentration in the outflow stream was measured continuously with a zirconia analyser until a steady-state condition was achieved. The diffusion coefficient was calculated according to the following equation:

$$D = \frac{QT}{A(C_2 - C_1)} \quad \text{Eq. 3.3}$$

Where:

Q = Oxygen diffusion rate at 1 bar (m³/s)

$$= \frac{R_1}{60 \times 10^6} \times \frac{G_1 - G_0}{100} \times (P_1 - P_2)$$

C_I = Mean concentration of oxygen in the nitrogen stream at 1 bar (m³/m³)

$$= \frac{G_0 + G_1}{2} \times \frac{P_1 - P_2}{100}$$

C_2 = Concentration of oxygen in the oxygen stream at 1 bar (m³/m³)

$$= \left(100 - \frac{R_1}{R_2} \times \frac{G_1 - G_0}{2} \times \frac{\sqrt{32}}{\sqrt{28}}\right) \times \frac{P_1}{100}$$

T = Thickness of sample (mm)

A = Cross-section area of sample (mm^2)

R_1 = Flow rate of nitrogen stream (mL/min)

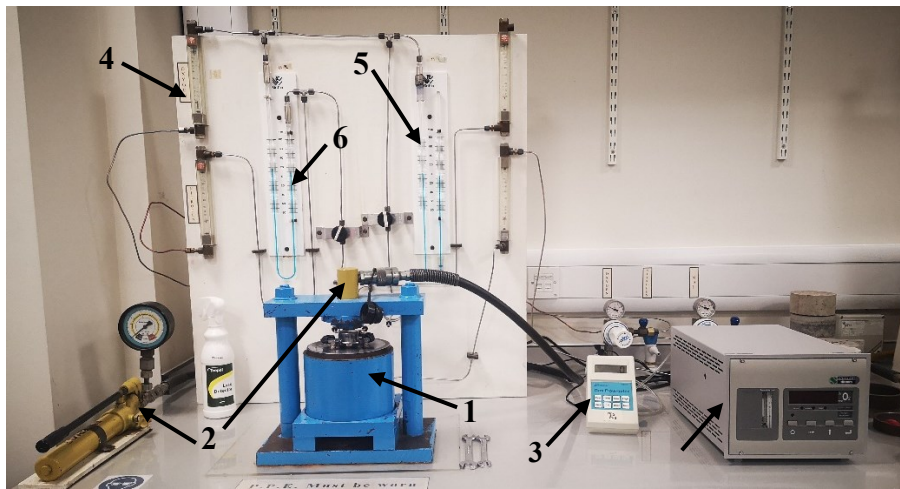
R_2 = Flow rate of oxygen stream (mL/min)

P_1 = Pressure of oxygen stream (bar)

P_2 = Pressure difference between the oxygen and nitrogen stream (bar)

G_0 = Percentage of oxygen in the initial nitrogen stream (0.004%)

G_1 = Percentage of oxygen in outflow stream



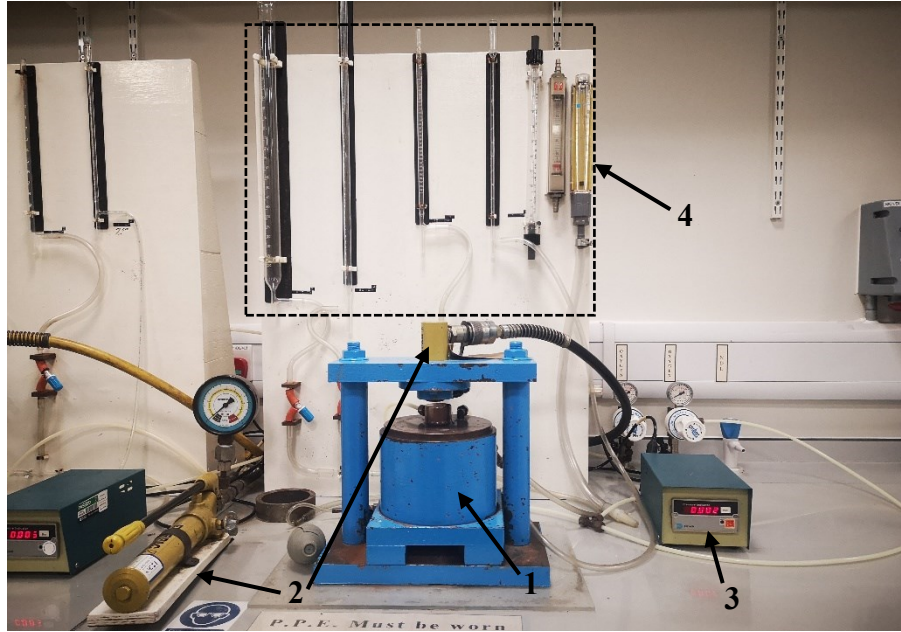
Notation: 1. Diffusion cell; 2. Loading jack; 3. Flow meter of nitrogen (R_1); 4. Flow meter of oxygen (R_2); 5. Manometer (P_1); 6. Manometer (P_2)

Figure 3.8 Oxygen diffusion test setup

3.4.2 Oxygen permeability

Permeation refers to the mass transport phenomena under pressure gradient. Oxygen permeability testing was conducted by exposing the top side of the sample to pressurised oxygen and measuring the outflow through its bottom side. The test rig shown in Figure 3.9 was used. Sample was first placed into the cell containing silicone rubber ring, followed by the application of 15 kN load to the lid of the cell to seal the sample. The top surface of the sample was exposed to oxygen gas at pressures of 0.5, 1.5 and 2.5 bars above atmospheric pressure respectively. At each applied pressure, the steady-state outflow rate was measured with soap

bubble flow meters. Four readings were taken and averaged. The maximum to minimum flow rate ratio was no more than 1.02.



Notation: 1. Permeation cell; 2. Loading jack; 3. Inlet pressure indicator; 4. Soap bubble flow meters

Figure 3.9 Oxygen permeation test setup

Intrinsic permeability coefficient k_{int} was used as the index of oxygen permeation for comparison in this study. To determine the intrinsic permeability coefficient k_{int} , apparent permeability coefficient k_g at each input pressure was first calculated with the following equation according to Darcy's law

$$Q = k_g \times \frac{A}{2\eta_v T} \times \frac{P_1^2 - P_2^2}{P_2} \quad Eq. 3.4$$

Where:

Q = Flow rate (m^3/s)

k_g = Apparent permeability coefficient (m^2)

A = Cross-section area of sample (m^2)

η_v = Gas viscosity (2.02×10^{-5} Ns/ m^2 for O_2 at $20^\circ C$)

T = Thickness of sample (m)

P_I = Absolute pressure on the inlet face (N/ m^2)

P_2 = Absolute pressure on the outlet face (N/m²)

According to the Klinkenberg correction (shown in Eq. 3.5), the calculated k_g was plotted against the $1/P_m$. The intrinsic permeability coefficient k_{int} was obtained from the y-intercept of the best-fit regression line.

$$k_g = k_{int} \left(1 - \frac{\beta}{P_m}\right) \quad \text{Eq. 3.5}$$

Where:

k_{int} = Intrinsic permeability coefficient (m²)

P_m = Mean pressure of the inlet and outlet streams (m²)

$$= \frac{1}{2}(P_1 + P_2)$$

β = Constant for a given material and gas

3.4.3 Water absorption

Water absorption refers to the ability of a porous material to absorb and transmit water under capillary suction (Hall, 1989). It was evaluated with a gravimetric method in this study as shown in Figure 3.10. The initial weight of the sample was measured and the sample was then placed in a tray with shallow water of about 3-5 mm above its bottom face. The weight of the sample was measured at intervals of 5, 10, 15, 20 and 30 mins, and then every 30 mins for the next 6 hours. Prior to each weighing, excess water on the surface of the sample was wiped off with a dampened cloth. To avoid water evaporation from the sample, the top of the tray was covered with a lid.

According to the classical non-saturated flow theory, cumulative mass of the absorbed water per unit area of the unidirectional inflow surface is linearly proportional to the square root of time, as expressed in Eq. 3.6. Therefore, cumulative absorbed water per unit area was plotted against the square root of time, and sorptivity coefficient was determined from the slope of the best-fit linear regression line according to the results obtained from the first 6.5 hours. An example of the plot and the regression is shown in Figure 3.11. The R^2 of the linear regression is generally larger than 0.99.

$$i = a + S(t)^{0.5} \quad \text{Eq. 3.6}$$

Where:

i = Cumulative absorbed water per unit area (g/m^2)

a = Constant for fitting

S = Sorptivity coefficient ($\text{g}/\text{m}^2\text{min}^{0.5}$)

t = Time (min)

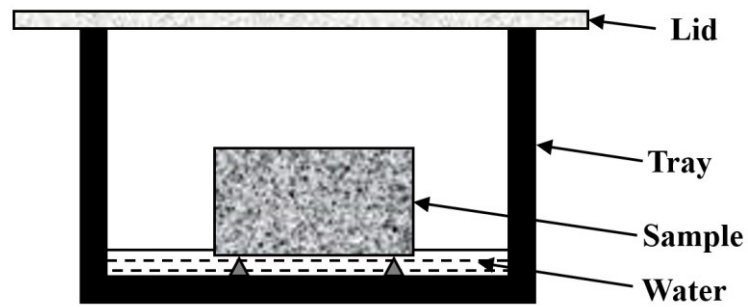


Figure 3.10 Water absorption test setup

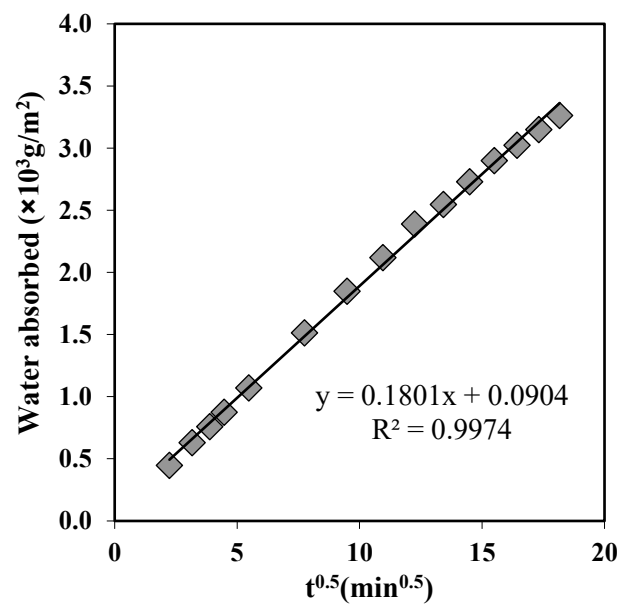
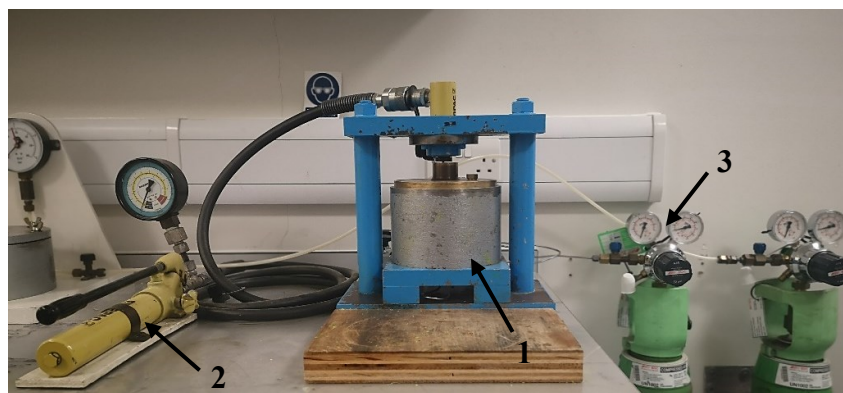


Figure 3.11 Example of water absorption plot and regression for water sorptivity coefficient

3.5 Fluorescent epoxy impregnation

This is another method to characterise transport property and to identify cracking in samples, especially at critical positions such as the spacer-concrete interface (Chapters 5 to 7). The test was done by impregnating a pre-dried sample with a low-viscosity fluorescein-dyed epoxy resin from one face under the air pressure (10 bar), and then imaging the cross-section under ultraviolet light for further analysis. The setup for fluorescent impregnation and the imaging are shown in Figure 3.12 and Figure 3.13, respectively.

Cylindrical samples with diameter of 100 mm and thickness of 50 mm were pre-conditioned at 50°C oven until constant weight ($< 0.01\%$ mass loss per day). The sample was then left to cool at room temperature, and wrapped with two layers of waterproof tape along their curved surfaces and two layers of clear tape along the perimeter of the bottom face. The aim of this was to prevent leakage of the epoxy from the curved surface of the sample. Subsequently, the sample was placed in the impregnation cell, with its bottom face up for epoxy penetration. A mixture of fluorescein-dyed epoxy resin, hardener and toluene at the mass ratio of 22:3:2 was then prepared and poured on to sample. A load of 15 kN was applied to the lid of the impregnation to seal the sample, as was done in the diffusivity and permeability testing. A 10-bar air pressure was then applied and maintained for 12 hours to push the epoxy into the sample. After the epoxy has hardened, the sample was extracted and sectioned at the position as shown in Figure 3.14. The freshly exposed cross-section was imaged with an Olympus SZX10 stereomicroscope at $1.5\times$ magnification and 20 ms exposure time. The impregnation depth was measured using image analysis with ImageJ.



Notation: 1. Impregnation cell; 2. Loading jack; 3. Pressure gauge

Figure 3.12 Fluorescent epoxy impregnation test setup



Notation: 1. Computer for monitoring; 2. Stereomicroscope; 3. Sample; 4. Movable platform

Figure 3.13 Setup for fluorescence imaging of the impregnated epoxy

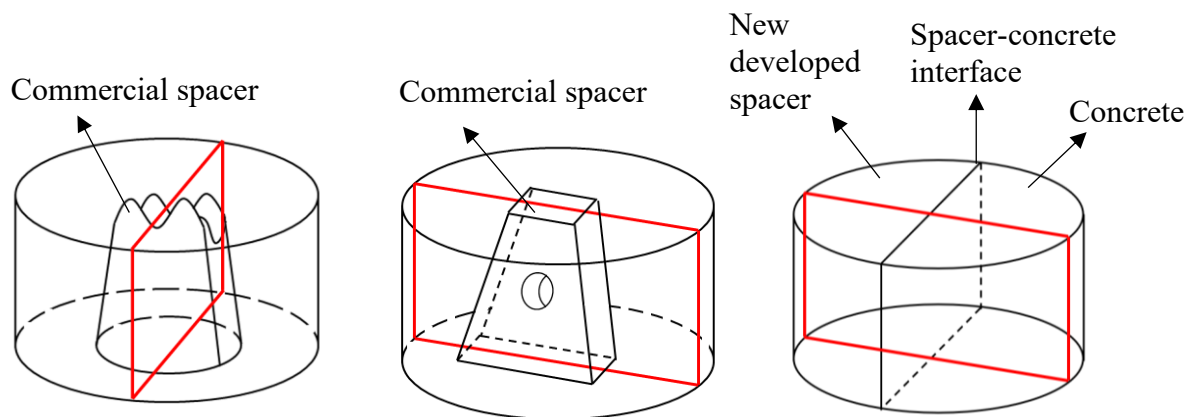


Figure 3.14 Cutting positions (marked in red) after epoxy impregnation for fluorescence imaging

3.6 Sample preparation for microscopy

To study the microstructure of commercial cementitious spacers (Chapter 4) and the interface between new developed spacers and concrete (Chapters 6 and 7), samples for microscopy analysis were prepared. A block of $40 \times 20 \times 8 \text{ mm}^3$ was first sectioned from the cast cylindrical samples containing spacers using a diamond precision cutter. For commercial cementitious

spacers, the block was extracted from the middle of the sample, with no inclusion of tie holes. Blocks for investigating the spacer-concrete interface was extracted from the sample used for fluorescent epoxy impregnation as shown in Figure 3.15. This is because the impregnated epoxy protects the spacer-concrete interface from potential damage during sample preparation. The block samples were then dried in 50°C oven until constant weight to remove any water absorbed during wet cutting.

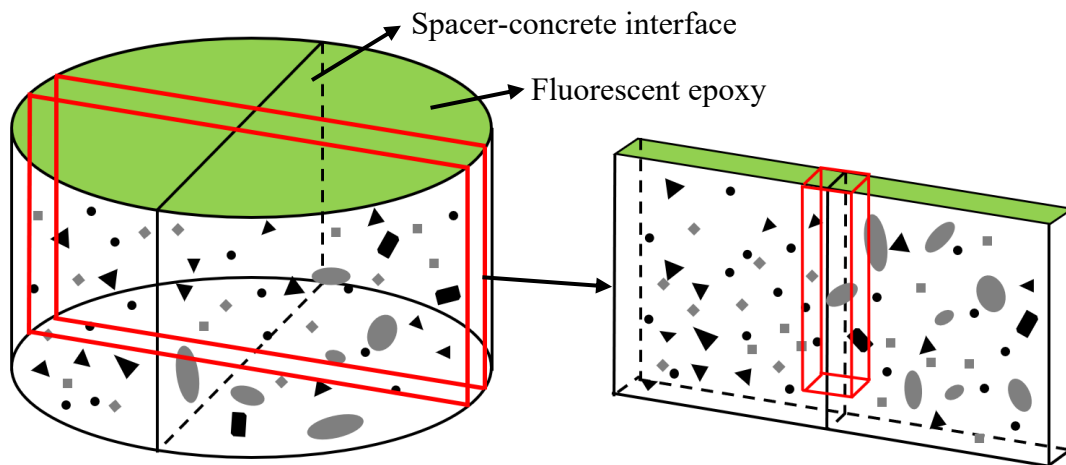
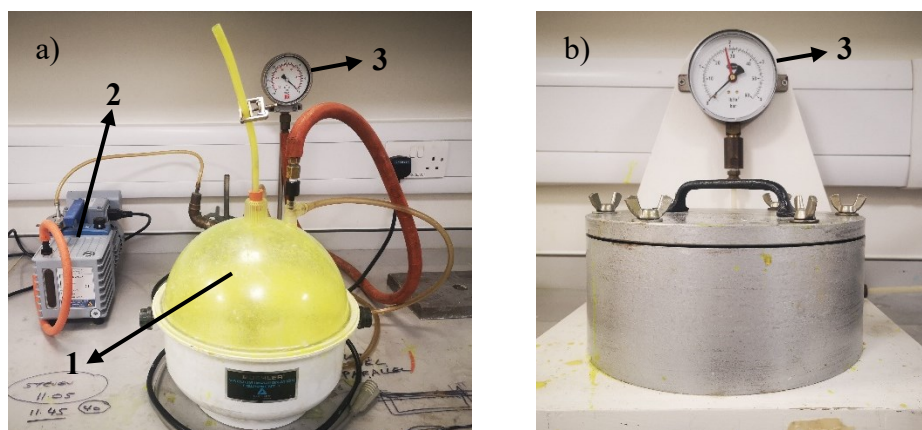


Figure 3.15 Extraction of a block sample (marked in red) for investigating the microstructure of spacer-concrete interface

The dried block was first encased with epoxy resin leaving only the surface for imaging exposed. The encasement protects the sample from damages during subsequent preparation. The encased sample was then transferred into a vacuum chamber for evacuation, as shown in Figure 3.16a. Fluorescein-dyed epoxy resin was mixed with hardener and toluene at mass ratio of 22:3:2. The epoxy was transferred into the vacuum chamber, de-aired and poured on to the block sample. After covering the entire surface of the block with epoxy, the vacuum was slowly released by allowing air into the chamber. The sample was then carefully placed into a pressure chamber as shown in Figure 3.16b. A 2.5 bar air pressure was applied inside the chamber for 1 hour. Excess epoxy was removed from the surface of the sample, and the impregnated sample was cured at room temperature until the epoxy has fully hardened.



Notation: 1. Vacuum chamber; 2. Vacuum pump; 3. Pressure gauge

Figure 3.16 Apparatus for: a) vacuum epoxy impregnation; b) subsequent pressurisation

The sample was then ground and polished in a series of steps using the Struers LaboForce-Mi machine, as shown in Figure 3.17a. Grinding was conducted with abrasive SiC paper with grades of 220, 500, 1000 and 2000 grit respectively. The samples were then polished using diamond abrasives with grit sizes of 9, 6, 3, 1 and 0.25 μm . These aimed at gradually removing scratches and other damages produced during the preceding sample preparation steps. At each stage, the sample was cleaned with acetone in ultrasonic bath and the surface of the sample was checked with Olympus BX51 microscope, shown in Figure 3.17b, to ensure they were well prepared. The polished samples were kept in a desiccator with silica gel at room temperature and taken out when required for imaging.

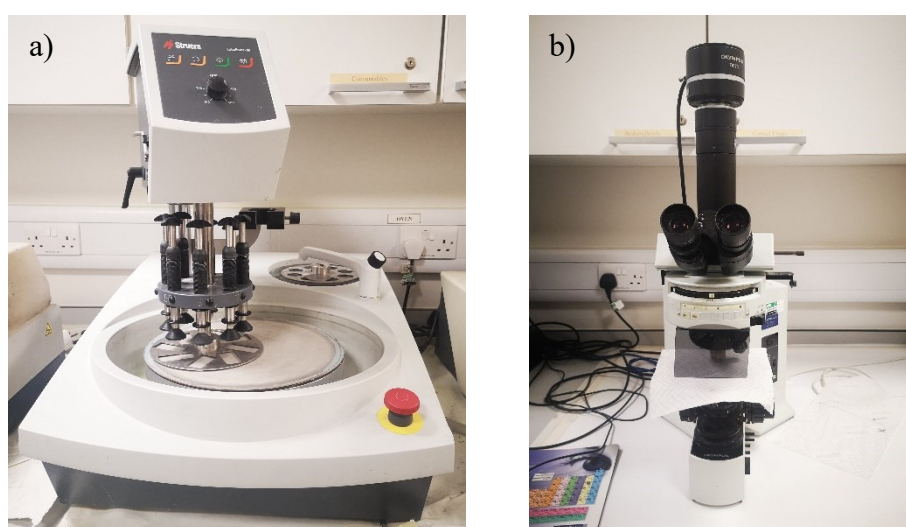


Figure 3.17 Setup for: a) grinding and polishing; b) monitoring sample preparation for microscopy

3.7 Summary

Main experimental procedures used in this thesis are presented in this chapter. Details of the materials used and a new method developed for producing spacers are described. Sample preparation, experimental apparatus and test methods for characterising the mechanical properties, mass transport and microstructure are detailed. Mix proportions and other unique test regimes (such as the carbonation resistance test in Chapters 4 and 7) used in each investigation will be presented in the experimental section of subsequent chapters.

Chapter 4 Properties of commercially available cementitious spacers

This chapter presents an investigation of the properties of commercially available cementitious spacers and their effects on the performance of concrete. Nine groups of cementitious spacers were obtained from five major spacer manufacturers from the UK and Germany. Properties that impact the quality and durability of concrete constructions were evaluated. These are categorised into three aspects: dimensional properties, mechanical properties, and durable properties. The study found a huge variation in properties between different spacers, especially regarding their impact on durability. The implications of this are discussed.

4.1 Introduction

In concrete construction, spacers are in high demand and widely used to ensure that embedded reinforcement is placed correctly and protected by the concrete cover. Spacers are left permanently cast in concrete and become part of the construction (Alzyoud et al., 2016). To build a safe and durable structure, the spacers should have the right size, sufficient strength, stiffness, and durability (Concrete Society, 1989). Generally, spacers are produced by specialist manufacturing companies. One commonly-used manufacturing method is to cast the spacers directly in moulds of special shapes (shown in Figure 4.1). Other methods are also used for spacer production such as concrete extrusion. Manufactured spacers are then supplied to local suppliers or construction projects. The contractor is usually responsible for selecting the type of spacers used.

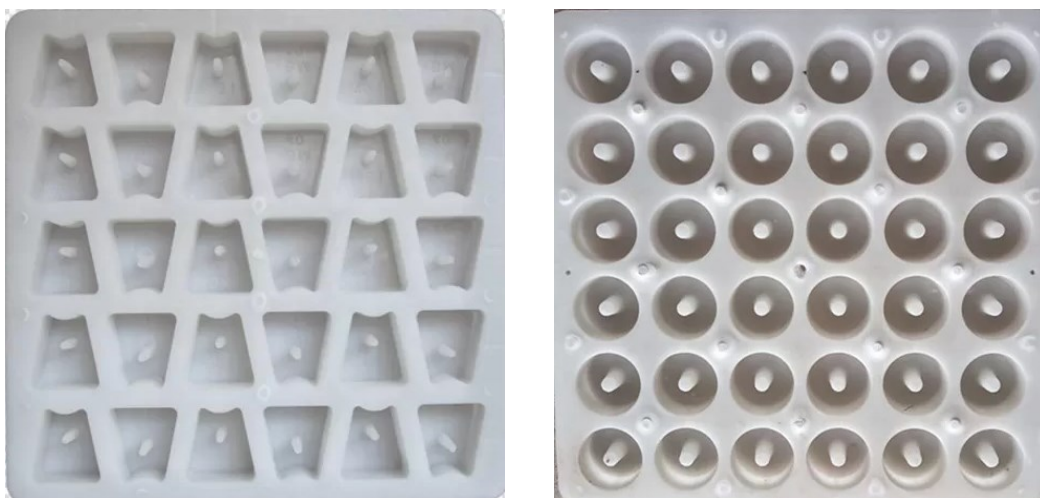


Figure 4.1 Plastic moulds for the manufacture of cementitious spacers (ZIH, 2022)

Many types of spacers can be found worldwide via numerous manufacturers and suppliers. A survey of spacers manufacturers carried out during this PhD (shown in Appendix I) found that generally, manufacturers provide information on their spacer's cover depth, price, and suitability for particular applications. Some suppliers provide strength descriptions, but the majority are lacking and vague, with statements such as 'the strength of the spacers is not less than that of the surrounding concrete'. A small number of suppliers offer technical data sheets. However, compositional and durability information for their products are rarely available. Moreover, the information provided by suppliers come directly from the original manufacturers. The manufacturing, transport and storage conditions are often overlooked, even though these will likely affect the performance of spacers.

Cementitious spacers generally have a higher load bearing capacity and similar thermal expansion/shrinkage to the surrounding concrete, compared to plastic spacers. Cementitious spacers are therefore widely used in concrete elements such as foundations and slabs. It is expected that the properties of cementitious spacers are highly dependent on the mix composition, processing, curing and exposure conditions since these are porous materials and likely to undergo degradation mechanisms over time, similar to other cement-based materials. A wide range of cementitious spacers is available on the market in terms of dimension, shape, composition, production procedure and curing condition. All these factors increase the diversity of their performance. However, the properties of cementitious spacers are generally neglected, and limited information concerning their impact on the performance of concrete structures are available. No systematic research studies have been carried out to evaluate the performance of cementitious spacers. Therefore, the aim of this chapter is to assess and compare the properties of a range of commercially available cementitious spacers in order to fill this knowledge gap.

4.2 Experimental

4.2.1 Spacers

A comprehensive survey on cementitious spacers available from manufacturers worldwide (shown in Appendix I) was carried out. Based on this survey, spacers from five leading European manufacturers were collected for this investigation with a consideration on the availability and reduction on additional biases introduced by long-distance delivery. Nine types

of spacers (100 replicates collected and 80 replicates tested for each type) were investigated, and they can be divided into two categories: single cover spacers (S) and mesh spacers (M), as shown in Figure 4.2. Both categories are in high demand according to the manufacturers, with the second category having higher load capacities for supporting reinforcement mesh. Spacers with embedded wires or clips and line spacers were not included in this study because they would require additional (impractical) preparation for fitting into our test apparatus. Spacers investigated in this study are nominated in the form of type followed by manufacturer number. For instance, ‘S1’ refers to single cover spacers from Manufacturer 1. Detailed information provided by the manufacturers is listed in Table 4.1.

Table 4.1 Spacers information provided by manufacturers

Spacer	Source	Cover (mm)	Dimensional Tolerance	Material	Compressive Strength (MPa)	Others
S1	HY-TEN Ltd. (UK)	50	-	Concrete	>40	Coefficient of expansion and contraction similar to that of concrete
M1		40/50				
S2	Straight 2 Site Ltd. (UK)	50	<5%	Cement; 0/4mm sand; Aggregate: Cement=3:1	>40	-
M2		40/50				
S3	Euro Accessories Ltd. (UK)	50	<5%	Cement; 0/4mm sand (MP); Aggregate: Cement=3:1	>40	-
M3		40/50				
S4	BS Specialist Products Ltd. (UK)	50	±5%	A blend of Portland cement, sand, coarse aggregates and additives	>40	-
M4		40/50				
S5	Max Frank GmbH & Co. KG (Germany)	50	±1mm	Fibre reinforced concrete	50	Permitted deformation: <1mm; Water absorption: <3% after 30 mins; Chloride diffusivity: $< 0.5 \times 10^{-12} \text{m}^2/\text{sec}$

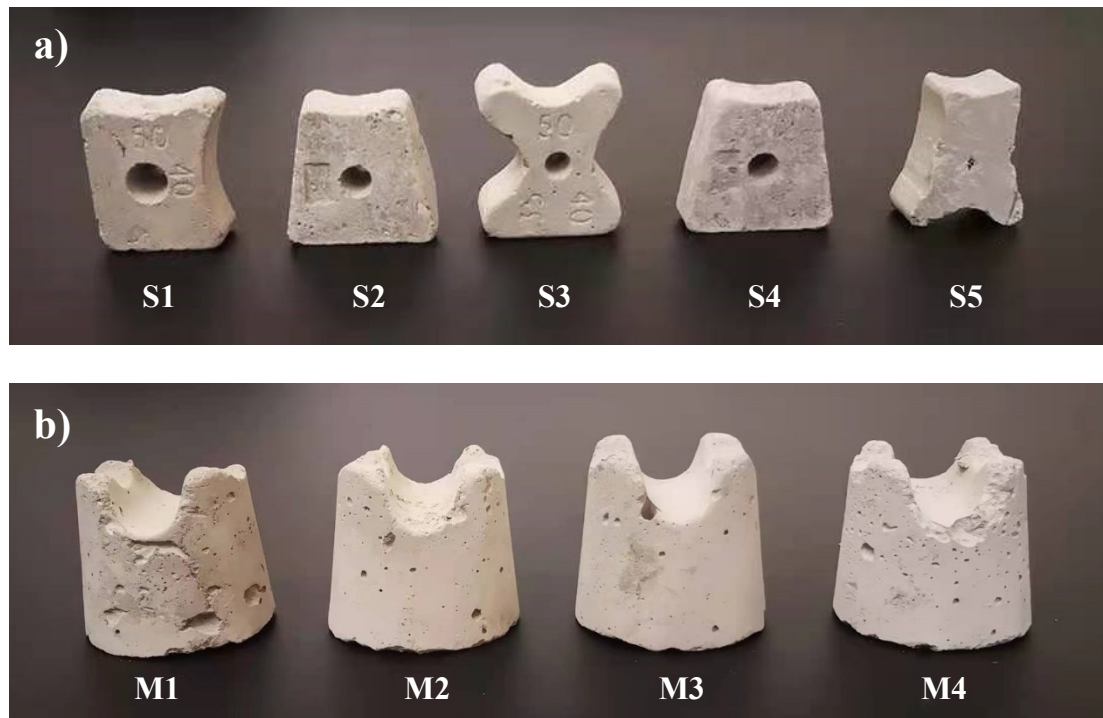


Figure 4.2 Spacers investigated in this chapter: a) S spacers; b) M spacers

4.2.2 Physical dimensions

Cover depth, thickness (for S spacers), diameter (for M spacers), cross-section area, volume, and density were measured. Figure 4.3 shows the typical measurements carried out. Cover depth (coincides with the construction), thickness and diameter were measured using electronic calliper with an accuracy of 0.01 mm. 50 replicates from each group of spacers were measured (25 replicates for S5 due to a lack of samples). It should be noticed that M spacers are designed with two cover depths and therefore both were recorded for analysis. Thickness of S spacers and diameter of M spacers of each replicate was based on averaging five measurements per spacer.

Measurement of the cross-sectional area was conducted for dimensional comparison and to provide the required information for water absorption testing. Cross-sections of S spacers were imaged with a stereomicroscope (Olympus SZX10) and the areas were measured through image analysis. Top and bottom cross-section areas of S spacers were recorded separately considering the different size of the holes for tying wires on each side. Cross-section areas of M spacers were calculated directly based on the measured diameter. The analysis was also divided into top and bottom sides due to the changing diameter with height.

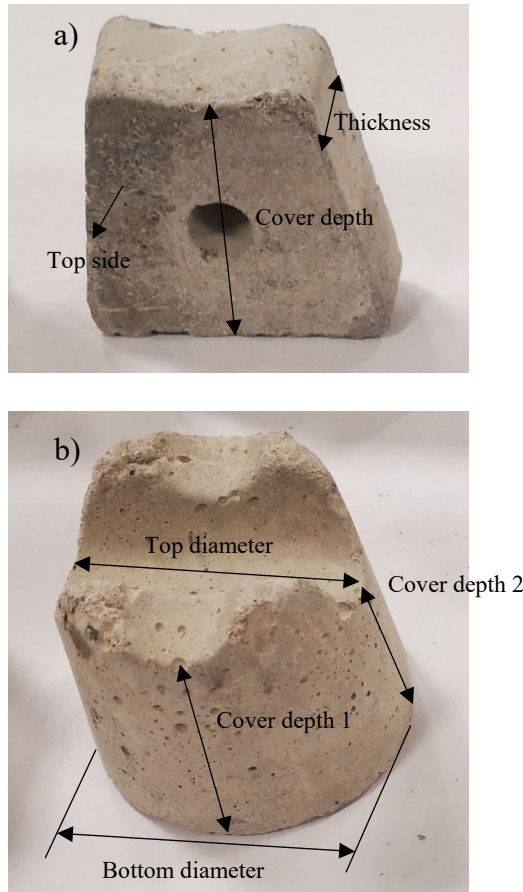


Figure 4.3 Physical dimension measurements: a) S spacer; b) M spacer

Volume was measured in order to calculate density and to provide a reference for the amount of concrete replaced in constructions. However, it is not possible to obtain volumes through simple calculations because of the irregular shape of the spacers. Therefore, three methods were used and compared initially. These are gas displacement pycnometry, 3D laser scanning and water displacement method.

Gas displacement pycnometry was performed with a Micromeritics AccuPyc II 1340 instrument. This consists of two sealable chambers of known volumes. The sample was sealed in one chamber and an appropriate volume of inert gas (helium) was admitted into this chamber. After recording the gas pressure in this chamber, the inert gas was expanded into the second chamber, which was previously in vacuum. The pressure in the second chamber was recorded and the sample volume was subsequently analysed. Five gas displacements were carried out and averaged to generate each result.

3D laser scanning was conducted with a Faro ScanARM with an accuracy of 0.1 mm. Samples were scanned, and their volumes calculated using the Geomagic Wrap software. Although the scanner was able to provide the outer contour of the spacers, it was limited in terms of detecting tie wire holes in the middle of S spacers (shown in Figure 4.4). Therefore, the volume of the tie hole was subtracted from the total volume measured by scanning to obtain the spacer volume. The volume of the tie wire hole was determined by multiplying its average area with the thickness of the spacer.

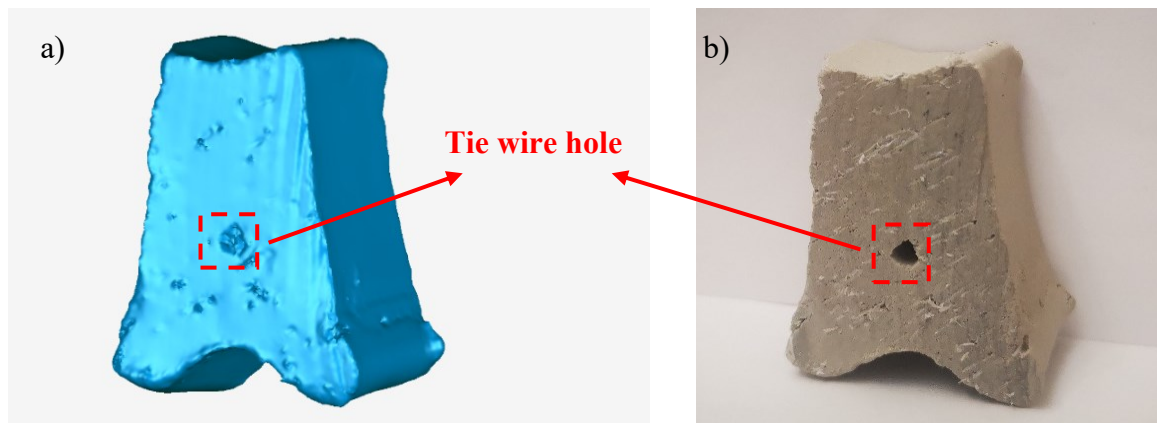


Figure 4.4 a) 3D laser scanned image and; b) ordinary camera photo of S spacer showing errors induced by the tie wire hole

Water displacement was accomplished by measuring the volume change when the spacer is submerged in water. To minimise the effect of water absorption into the spacers, a thin layer of wax was applied to the surface of the spacers before the test, and the test was completed as quickly as possible. Mass differences were within 0.01% before and after applying the wax.

The volumes derived from the above three methods are given in Table 4.2. As can be seen from the table, gas pycnometry generally gives much higher volumes, while the other two methods provide comparable results. It is suspected that gas pycnometry is not suitable for spacers because the spacers could not fill at least 2/3 volume of the test chamber for achieving accurate measurement according to the instrument manual. This also coincides with the finding that higher fill volume of the chamber is more beneficial for obtaining measurement of higher precision and accuracy (Nguyen et al., 2019). For the rest of this chapter, the water displacement method will be used because it is easier for conduct compared to 3D laser scanning. Density of spacer was calculated by dividing its measured mass to volume.

Table 4.2 Comparison of sample volume obtained from different methods

Spacer	Replicate	Volume (cm ³)		
		Gas pycnometry	3D laser scanning	Water displacement
S5	1	59.6	34.8	34.5
	2	60.0	36.0	35.2
	3	60.0	35.9	35.2
M1	1	140.2	85.1	85.1
	2	137.7	81.2	81.1
	3	134.3	79.0	79.0

4.2.3 Mechanical properties

Compressive strength, modulus of rupture, and dynamic Young's modulus of the spacers were measured following the procedures described in Chapter 3.3. Since the spacers were irregular and inconsistently shaped, they were sectioned with a diamond precision saw into regular cubes and prisms for the tests. All samples were immersed in water until constant weight before testing to minimise the effect of humidity on the measurements.

Details of each test such as the sample size and number of replicates are summarized in Table 4.3. It should be noted that the sample size shown in the table are approximate. The actual size of each sample was measured and used to calculate its mechanical properties. The sample size for each test was determined by considering the instrument requirements and taking into account the shape and the maximum spacer allowance. For each test, three replicate spacers were selected at random. Multiple samples were taken from each spacer for each test, and the number of replicate samples was determined by the maximum number that could be extracted from each spacer.

Table 4.3 Details of mechanical property tests

Property	Sample size	Number of replicates from each spacer	Test method	Load rate (mm/min)
Compressive Strength	15 × 15 × 15 mm ³	4	Cubic compressive strength test	0.2
Modulus of Rupture	5 × 5 × 24 mm ³	6	Third point bending	0.2
Dynamic Young's Modulus	30 × 30 × 15 mm ³	1 (tested four times)	Resonant frequency and damping analysis	-

4.2.4 Water sorptivity and accessible porosity

Water sorptivity was tested by monitoring the mass of water uptake through unidirectional water absorption. Test set up is shown in Figure 4.5. Three replicate samples were tested for each group of spacers. As described in Chapter 4.2.2, the cross-sectional area of each spacer was measured prior to the water sorptivity test and used as the inflow area in the subsequent analysis. To avoid potential errors related to the water displacement method, the volume of each spacer was calculated from its mass divided by the density as determined in Chapter 4.2.2.



Figure 4.5 Water sorptivity test setup

Prior to the test, all samples were conditioned at 50°C in the oven until constant mass and then cooled to room temperature. Each sample was weighed to record its initial mass and placed on two plastic strips fixed on the test tray, with one side accessible for water absorption. Water was carefully added to the tray up to a level of 3 mm above the sample inflow surface. The mass of the samples was measured at intervals of 5, 10, 15, 20 and 30 minutes, and then every 30 minutes for the next 6 hours. Mass gain per unit inflow area was plotted against the square root of the corresponding time, and water sorptivity coefficient was determined by calculating the slope of the best-fit line. Additionally, the coefficient of determination R^2 was plotted as a measure of the regression. R^2 was found to be larger than 0.99 in most cases.

After the water sorptivity test, samples were fully immersed in water and placed in a vacuum chamber for another 5 hours until complete saturation, as shown in Figure 4.6. The saturated samples were surface-dried and weighed. The accessible porosity was calculated from the mass change between the conditioned state and the vacuum saturated state as:

$$\varphi = \frac{m_s - m_c}{\rho_w V} \times 100\% \quad \text{Eq. 4.1}$$

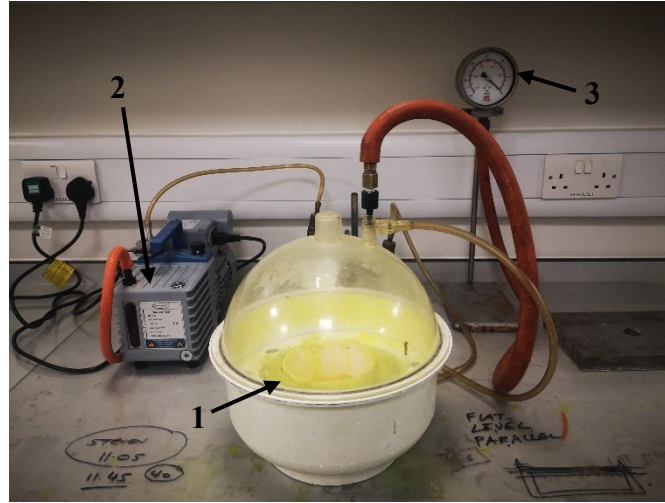
Where φ = Accessible porosity (%)

m_s = Mass of the sample at vacuum saturated state (kg)

m_c = Mass of the sample at conditioned state (kg)

ρ_w = Density of water at 20°C (1000 kg/m³)

V = Volume of the sample (m³)



Notation: 1. Vacuum chamber; 2. Vacuum pump; 3. Pressure gauge

Figure 4.6 Accessible porosity test setup

4.2.5 Carbonation depth and area

The initial carbonation depth of the as-received spacers and the subsequent carbonation resistance were investigated. Upon receiving the delivery from suppliers, six samples from each group of spacers were selected and conditioned at 75% RH, 20°C in a conditioning chamber containing soda lime (to prevent further carbonation). After reaching constant weight, three replicate samples were sectioned from the middle to expose a fresh surface, then dried with absorbent tissue and sprayed with phenolphthalein indicator to estimate the original carbonation depth. The remainder three replicate samples were transferred into a carbonation

chamber at 3% CO₂, 75% RH and 20°C for accelerated carbonation. After 28d, these were sectioned from the middle and tested with phenolphthalein to assess the carbonation resistance of different spacers.

Carbonated regions do not change in colour after application of phenolphthalein while non-carbonated regions tend to show a pink or purple hue. The cross sections were imaged using a stereo microscope and the extent of carbonation was measured using image analysis with the ImageJ/Fiji software. Both carbonation depth and area ratio were measured and compared. For S spacers, twenty measurements of carbonation depth were conducted on each sample. For M spacers, measurement of carbonation depth was carried in four regions as shown in Figure 4.7, with five measurements taken for each region and averaged. It is worth noting that measurement of S spacers was not categorized with regions, since the cross sections of such spacers are highly variable, and it is hard to establish a consistent rule for region classification.

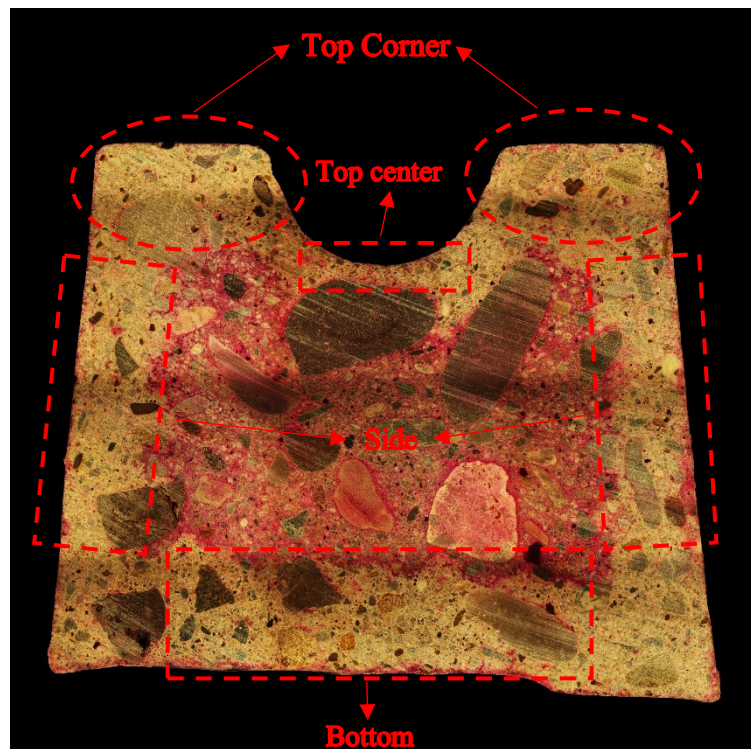


Figure 4.7 Regions for carbonation depth measurements for M spacers

The carbonation area ratio is defined as the ratio between the carbonated area and the entire cross-sectional area. The images were taken with spacers placed on a black plate to facilitate segmentation of the entire spacer with ImageJ by setting a suitable threshold. Segmentation of

the carbonated regions was done by splitting the RGB image from stereomicroscopy into its respective channels: red, green and blue. The non-carbonated regions are close to magenta, which is a complementary colour to green. Consequently, the non-carbonated regions appear dark in the green intensity image, as shown in Figure 4.8b. It is therefore possible to segment the non-carbonated regions by selecting an appropriate threshold level, and thus estimate the carbonated area by subtraction. However, segmentation errors could arise due to the colour of certain aggregate particles, especially when they are near the boundary between carbonated and non-carbonated regions, as shown in Figure 4.9. Therefore, each segmented image was visually checked, and such errors were manually corrected by picking out the problematic particles and subtraction.

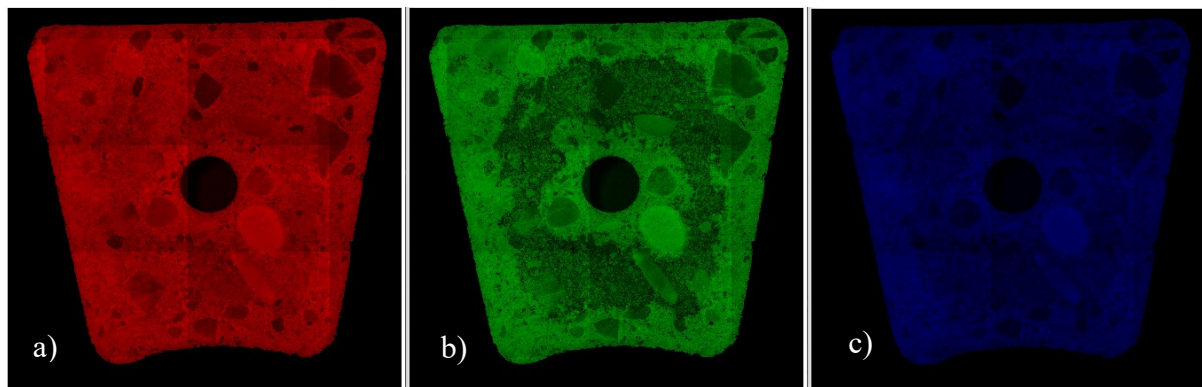


Figure 4.8 RGB images after splitting colour channels: a) red; b) green; c) blue

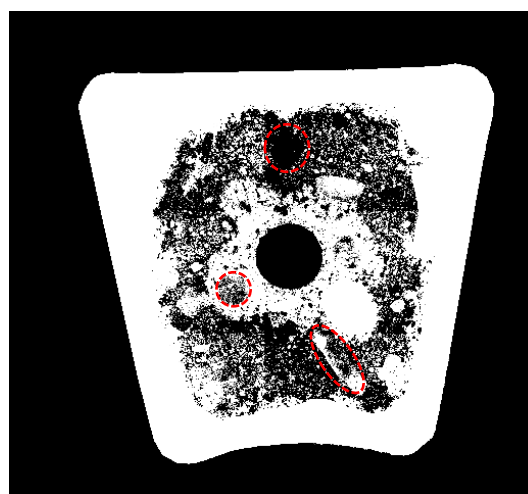


Figure 4.9 Possible segmentation errors caused by certain aggregate particles in the carbonated regions

4.2.6 Scanning electron microscopy and X-ray microanalysis

The basic constituents of spacers and their microstructure, such as porosity, anhydrous binder content, and aggregate volume fraction, were characterised using scanning electron microscopy (SEM) in the backscattered electron (BSE) mode and energy-dispersive X-ray microanalysis (EDX). Two small blocks of $40 \times 20 \times 8 \text{ mm}^3$ were extracted from each spacer. The block samples were dried in the oven at 50°C , then encased with epoxy, fully impregnated with fluorescein-dyed epoxy resin, then ground and polished at a series of finer grades. Full description of the sample preparation for microscopy is given in Chapter 3.6. A Hitachi TM4000plus SEM was used for the analysis. The SEM was operated at an accelerating voltage of 10 kV for image collection and 15 kV for EDX analysis.

BSE images were captured at $500\times$ magnification for measurement of porosity and anhydrous binder content. The images were digitized to 2560×1920 pixels at a pixel spacing of $0.099 \mu\text{m}$. Fifty images were collected from one sample initially to determine the number of images required to achieve a representative analysis. As shown in Figure 4.10, the measured porosity and anhydrous binder content gradually stabilised after around 15 images were analysed and averaged. To ensure that the results are reliable, thirty images were taken and analysed from each sample in this chapter.

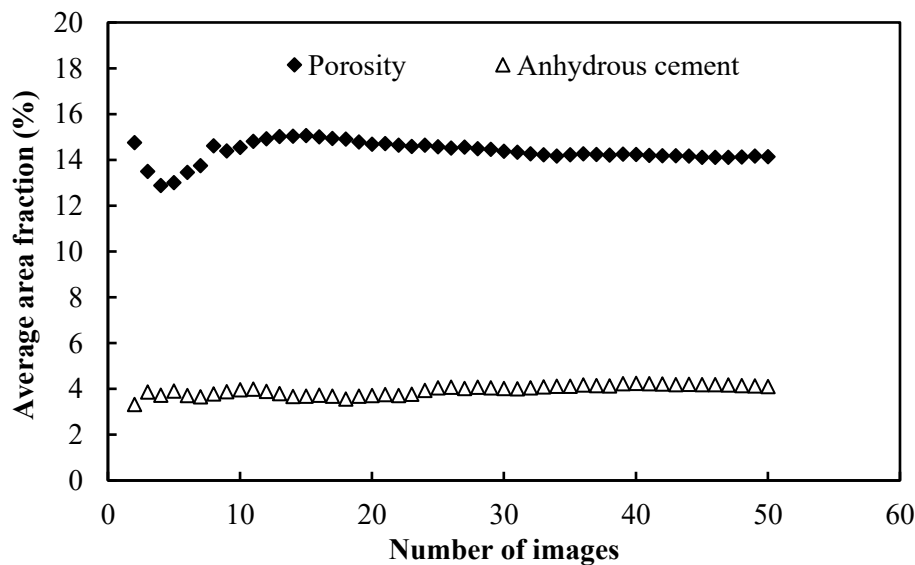


Figure 4.10 Measured porosity and anhydrous cement content with number of analysed images

In BSE images, the brightness intensity of each pixel depends on the mean atomic number of the underlying phase. Thus, phases with high atomic contrast such as pores and anhydrous

binders can be segmented by thresholding the image brightness histogram and measured via image analysis. It should be noted that the porosity and anhydrous binder content measured via image analysis refer to the area fraction of pores and unreacted binders in the cement paste, expressed as a percentage. Aggregates were segmented manually using ImageJ/Fiji on enlarged images so that the boundaries of aggregates could be easily traced.

Figure 4.11 shows BSE images and brightness histograms (aggregates removed) from two representative samples with different binders. The analysed porosity includes capillary pores and microcracks. These are filled with epoxy resin which has the lowest mean atomic number, and therefore appear as the darkest phase in the BSE image. The lower threshold value was set as zero and the upper threshold was determined via the overflow method (Wong et al., 2006). Binders observed in the investigated spacers consist mainly of Portland cement and GGBS particles. These are brighter than the other phases in the image and they generate peaks at the higher end of the greyscale histogram. Consequently, the threshold values for the anhydrous binders were determined by selecting the minimum grey value between the respective peaks for Portland cement and GGBS.

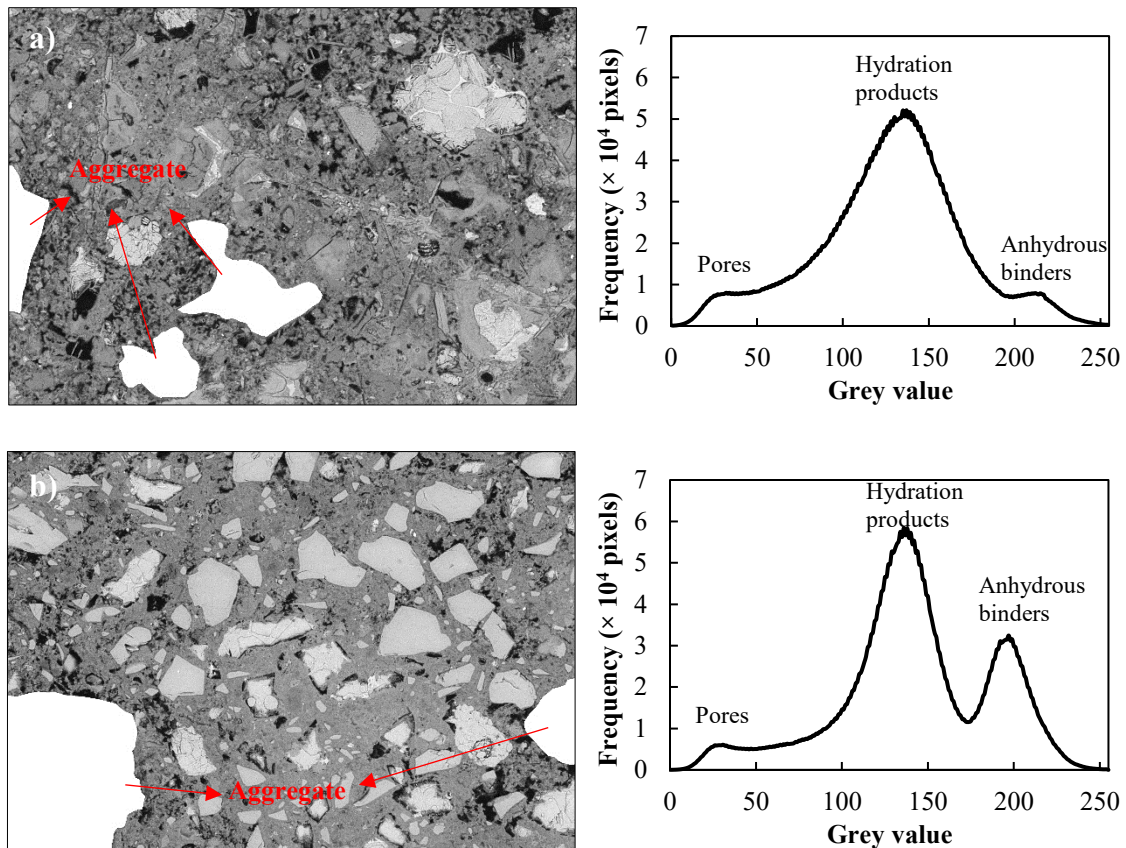


Figure 4.11 BSE images and brightness histogram for phase segmentation from samples with different binder types: a) Portland cement; b) GGBS & Portland cement

Aggregate content in spacers was measured via a point-counting method. BSE images were captured at 300 $\times$ magnification and digitised to 2560 $\times$ 1920 pixels at a pixel spacing of 0.165 μ m to give a larger field of view. A regular grid with certain number of grid points was overlaid on the BSE images. The number of points that intersect the aggregate phase was counted and divided by the total number of overlaid grid points to obtain the aggregate volume fraction. Figure 4.12 shows the effect of number of grid points and number of analysed images on the measured aggregate content of a particular cementitious spacer sample. It is observed that the number grid points within the selected range had a marginal effect on the measured aggregate volume fraction, especially when more than fifteen images were counted and averaged. Therefore, it was decided that the analysis of aggregate volume fraction will be carried out using 108 grid points superimposed on each image and a total of thirty images analysed per sample.

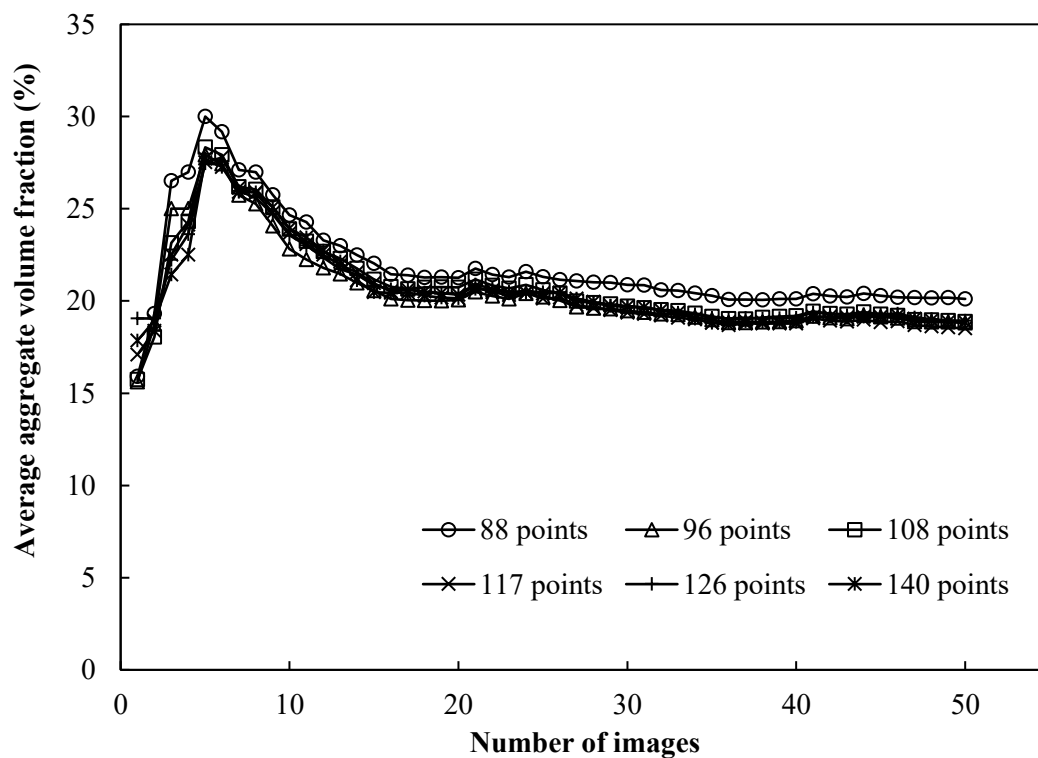


Figure 4.12 Effect of number of grid points and analysed images on the measured aggregate volume fraction

4.3 Results and discussion

4.3.1 Physical dimensions

The measured cover depths of spacers according to the results from 50 replicates (25 replicates for S5) are shown in Figure 4.13 (data from each replicate are tabulated in Appendix II). Dimensional tolerance according to BS 7973-1 (2001) is marked with red lines. It can be observed that except for S1, around 80% of S spacers had cover depths within allowable tolerance. The majority of those with cover depths outside of the tolerance were larger than their specified value (50 mm). This might not cause disadvantages in terms of durability or fire protection, but it could lead to an inaccurate placement of reinforcement and load carrying capacity. In contrast, cover depths of all tested M spacers were 6% to 22% smaller than their specified value (40 or 50 mm). This could clearly lead to an insufficient protection against reinforcement corrosion.

Other physical dimensions are summarised in Table 4.4. Thickness of each S spacer type was calculated based on the average of 50 replicates. The replicate spacers had very similar thickness as indicated by the small standard deviation. S spacers from different manufacturers had similar thickness that ranged within 20-25 mm. However, the cross-sectional areas of spacers from different manufacturers were different due to the diverse shape of these spacers. Another interesting finding is the difference between the top and bottom surface areas of S spacers. S1 spacers had the highest difference, which was approximately 695.8 mm², while the difference for S5 spacers was only about 12.3 mm². This is mainly due to the non-uniform size of tie wire hole alongside the thickness of S spacers. The gradually enlarged cross sections might be friendly for the wire tiring. However, it could also bring unknown effects on concrete compaction.

In contrast, the M spacers had similar cross-sectional areas, with top and bottom cross-sectional areas of around 1670 mm² and 2400 mm² respectively. It is worth noting that the bottom side of M spacers are likely to be exposed on the surface of concrete elements. This could induce both aesthetic and durable effects to the structure, depending on the colour and property differences between these spacers and the surrounding concrete. The volume of M spacers also showed less variation. However, M spacers are larger than S spacers (up to 130%), and therefore the inclusion of M spacers is likely to bring a greater impact on the performance of the structure.

Density of all tested spacers ranged from 1833.0 to 2457.1 kg/m³, which is within a typical density range for cementitious materials. M spacers had slightly higher density than S spacers, probably due to a higher aggregate volume fraction in M spacers.

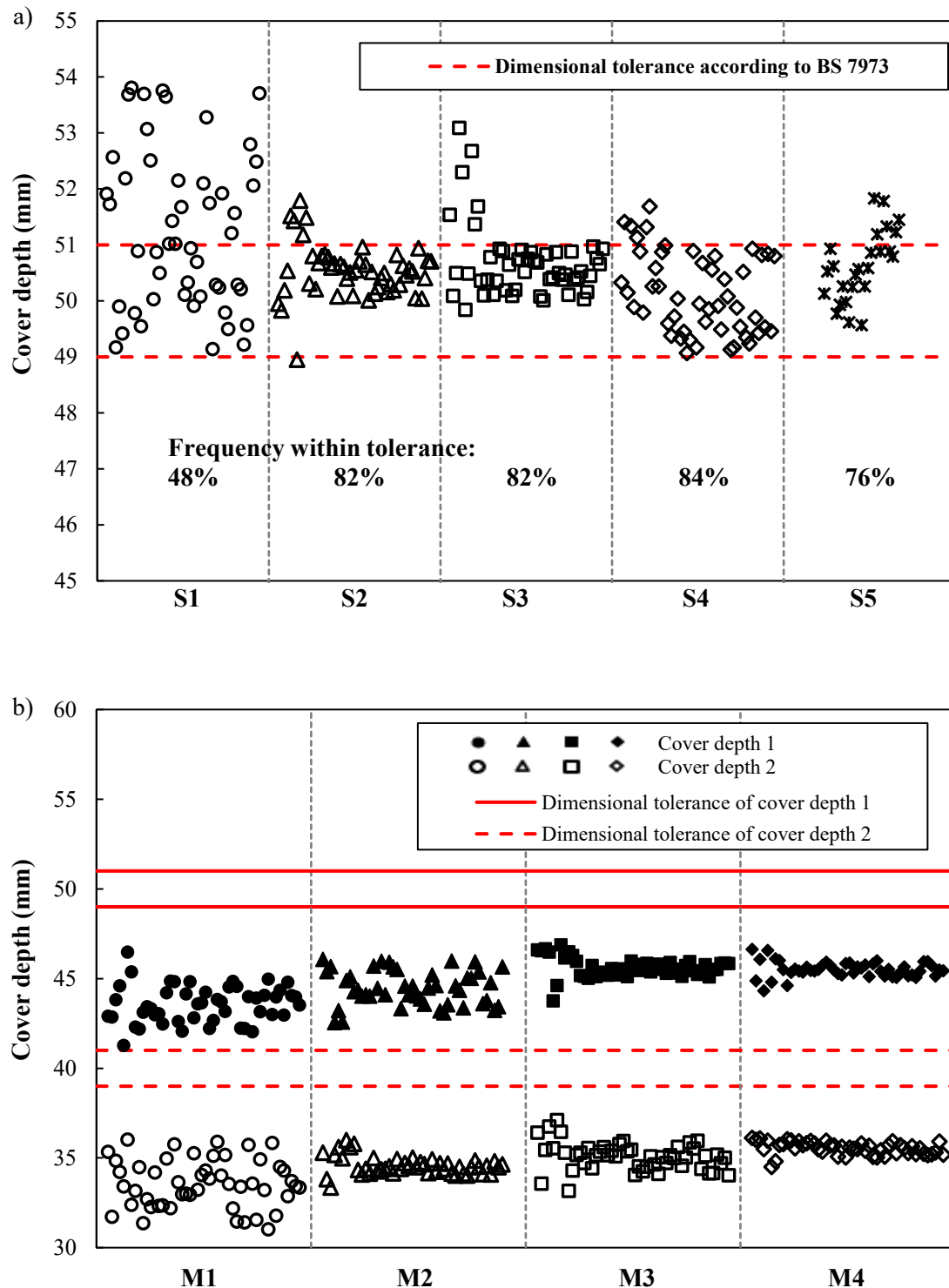


Figure 4.13 Cover depth results and tolerance according to BS 7973: a) S spacers; b) M spacers

Table 4.4 Physical dimensions of spacers

Spacer	Thickness (mm)	Top area (mm ²)	Bottom area (mm ²)	Average area (mm ²)	Volume (mm ³)	Density (kg/m ³)
S1	22.7 (0.1)	1941.3 (21.0)	2637.1 (103.5)	2289.1	51360 (4218.9)	2202.4 (302.5)
S2	20.7 (0.5)	2422.1 (29.5)	2730.8 (45.3)	2576.5	58477 (196.0)	1833.0 (17.6)
S3	23.2 (0.1)	2214.9 (113.3)	2588.5 (72.1)	2401.7	49450 (2471.5)	2166.9 (96.5)
S4	20.5 (1.1)	2395.0 (183.8)	2706.0 (51.2)	2550.5	51383 (5490.3)	2005.6 (192.8)
S5	24.9 (0.1)	1721.4 (236.1)	1733.7 (215.8)	1727.5	35240 (735.1)	2228.1 (7.7)
M1	-	1647.7 (30.2)	2366.5 (40.7)	2007.1	73240 (2385.5)	2385.5 (22.6)
M2	-	1675.7 (14.6)	2424.0 (6.5)	2049.9	75787 (829.9)	2358.3 (27.0)
M3	-	1667.1 (9.4)	2428.8 (22.2)	2048.0	81067 (693.3)	2302.3 (68.4)
M4	-	1663.2 (1.0)	2393.9 (61.7)	2028.54	74993 (4715.2)	2457.1 (48.3)

Note: Average area refers to the average of top and bottom area; Standard deviation of each characteristic is listed in the brackets.

4.3.2 Mechanical properties

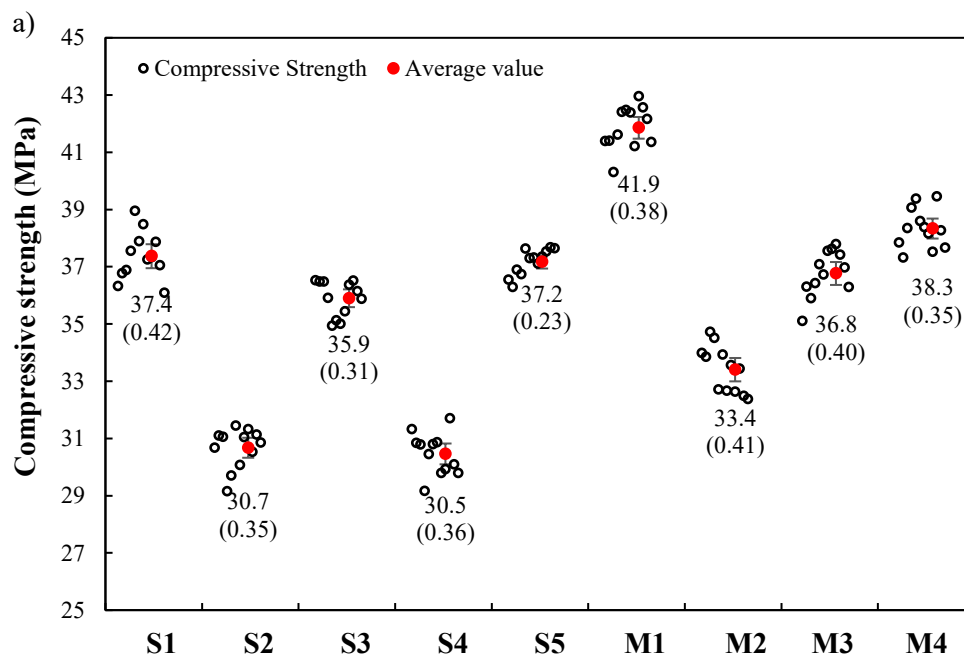
Test results for mechanical properties are shown in Figure 4.14. Detailed raw data including the measured dimensions of each cut sample are tabulated in Appendices III and IV. Average value and standard deviation (in brackets) are marked at the bottom of each type of spacer. Compressive strength, modulus of rupture and dynamic Young's modulus ranged from 29.2 to 43.0 MPa, 4.0 to 7.8 MPa and 1.8 to 2.5 GPa respectively.

There are clear differences in mechanical properties between the different types of spacers (up to a factor of 1.8 for modulus of rupture, and 1.4 for compressive strength and dynamic Young's modulus). Coefficient of variation (COV) for each property was calculated for quantifying the variation between different spacers. Modulus of rupture (COV of 17.1%) showed the highest variation following by the compressive strength (COV of 10.3%) and dynamic young's modulus (COV of 10.0%). Reasons of the differences could be complicated

and remains unknown due to a lack of information on their compositions, curing and storage conditions etc.

Compressive strength of all tested spacers were below the minimum requirements (50 MPa at 28 days) regulated in the British Standard (BS 7973-1:2001, 2001). The insufficient strength could lead to damages of spacers during construction. Minor damages such as microcracking, especially inside the spacers, are likely to be undiscovered or dis-concerned. The use of such spacers would undoubtedly bring negative effects on the durability of concrete structures. Major damages e.g. local crushing are easy to be observed and therefore such spacers could be replaced before concreting. Yet this is an obvious waste of labour and material.

Figure 4.15 plots average modulus of rupture and dynamic Young's modulus vs. compressive strength of different spacers. Compressive strength is observed to be dependent on the rest two mechanical properties. It indicates that spacers with higher compressive strength tend to have larger modulus of rupture and dynamic Young's modulus. A stronger correlation is observed when excluding the obviously scattered points (marked in red), which showed significantly lower modulus of rupture and dynamic Young's modulus respectively. This is likely to be attributed to different mix composition such as the inclusion of fibre (S5 in Figure 4.15b).



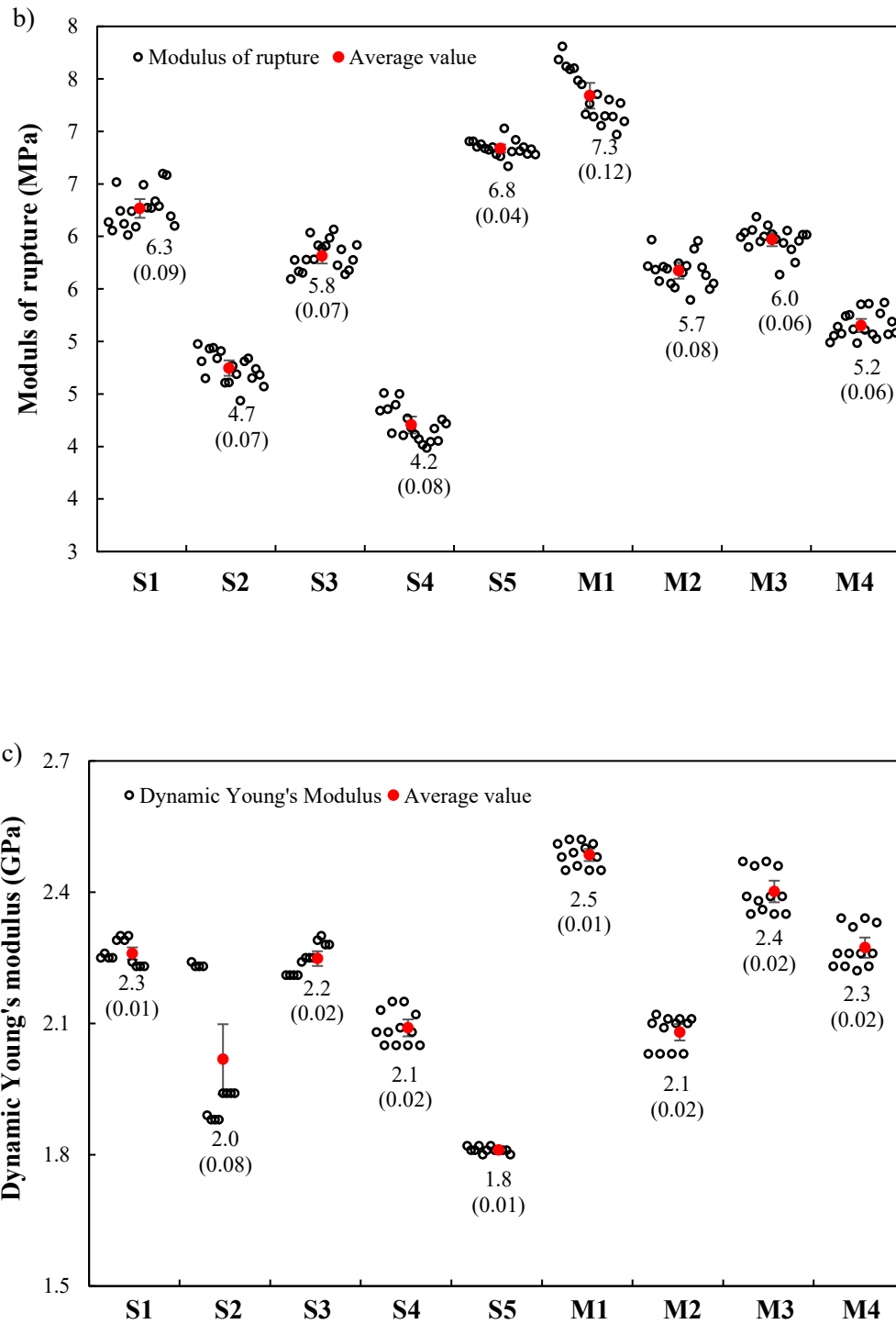


Figure 4.14 Mechanical properties of spacers: a) compressive strength; b) modulus of rupture; c) dynamic Young's modulus

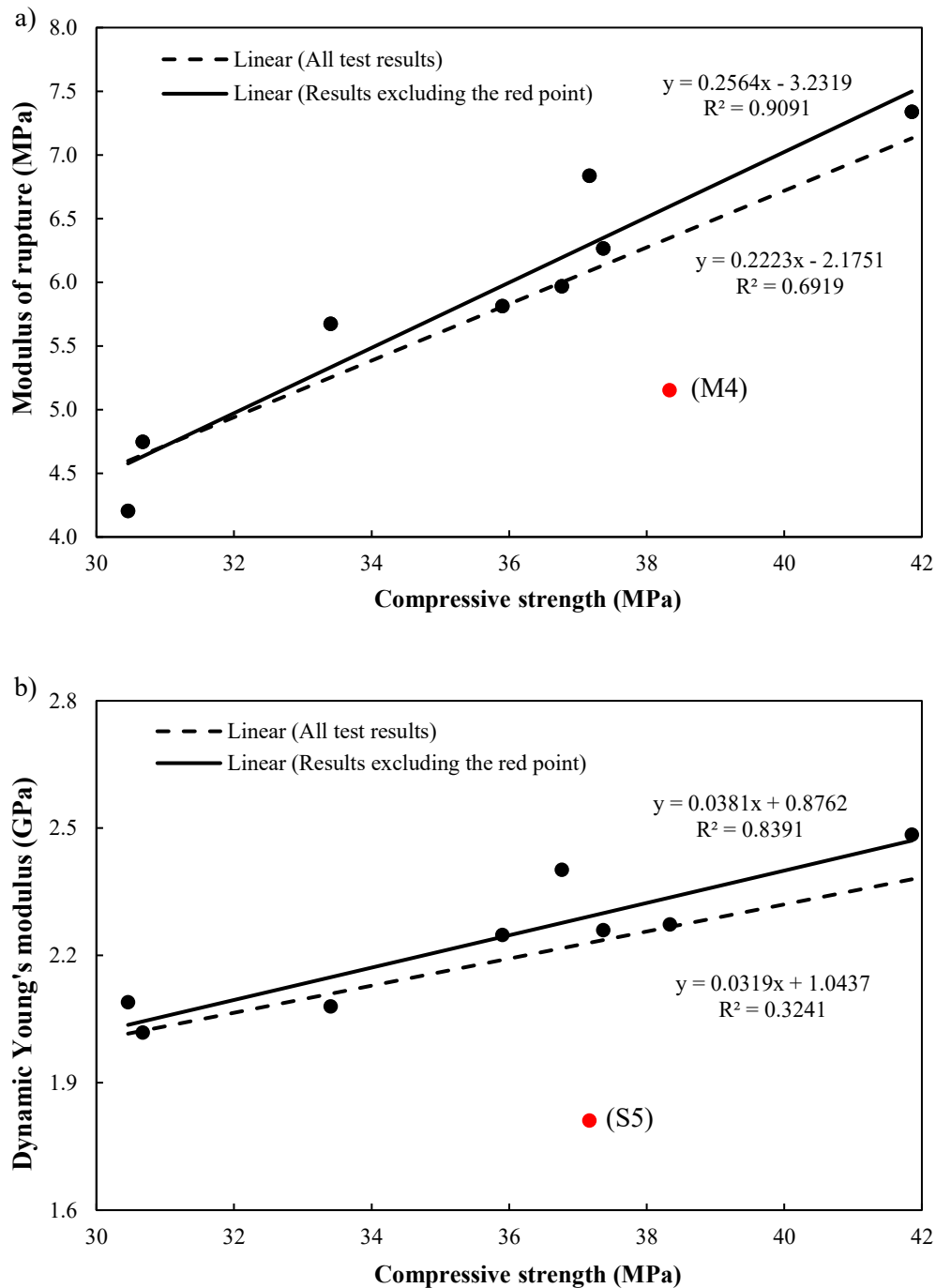


Figure 4.15 Correlation between compressive strength and: a) modulus of rupture; b) dynamic Young's modulus

4.3.3 Mass transport properties

Figure 4.16 plots water sorptivity coefficients vs accessible porosity of all tested spacers. A strong correlation was observed showing that spacers with higher water sorptivity coefficients

also had higher accessible porosity. This coincides with the well-known knowledge that water absorption occurs through interconnected (accessible) pores and cracks. It also shows that the testing methods were able to detect the changes of sorptivity and porosity in different spacers.

Average water sorptivity coefficient and accessible porosity from vacuum saturation for each spacer type are shown in Figure 4.17. Obvious differences were observed between different groups of spacers in terms of both properties. Sorptivity coefficients ranged over a factor of 10, from 17.6 to 247.2 $\text{g/m}^2\text{min}^{0.5}$ with the maximum-to-minimum ratio of 14.1 and the COV of 63.1%. Accessible porosity ranged between 4 and 21%, with the maximum to minimum ratio of 4.8 and COV of 43.5%.

Sorptivity coefficients and accessible porosity of M spacers were higher than the respective values of S spacers. Even for spacers that came from the same manufacturer, the sorptivity coefficient of M spacers was 1.3 to 14.1 times that of S spacers, and the accessible porosity of M spacers was 1.1 to 4.8 times the value of S spacers. This is worthy of special attention since M spacers are widely used in heavy load bearing applications, and in ground slabs and foundations, which may be exposed to the aggressive environments.

Additionally, many large air voids, chips and fractures were observed on the surfaces of M spacers, as shown in Figure 4.18 (and also Figure 4.2) compared to S spacers, and this feature occurred regardless of the manufacturer. The reasons for this remain unclear, but the observation suggests lack of good compaction during casting and possibly damages induced during demoulding, curing, storage, or delivery etc. These open voids and fractures were not considered in the sorptivity and accessible porosity under current testing regimes. Therefore the actual sorptivity and accessible porosity could be even higher than the measured values. In addition, their effects on the durability of concrete structures could be two-fold and are yet to be established fully. On the one hand, surface air voids and fractures might provide additional surface roughness and therefore benefit the spacer-concrete bonding. On the other hand, it might be difficult to compact concrete into or around these voids and fractures, and thus increasing the porosity of the spacer-concrete interface. Furthermore, the voidage and fractures seen on the surface are expected to exist inside the spacer too, which would negatively impact its performance.

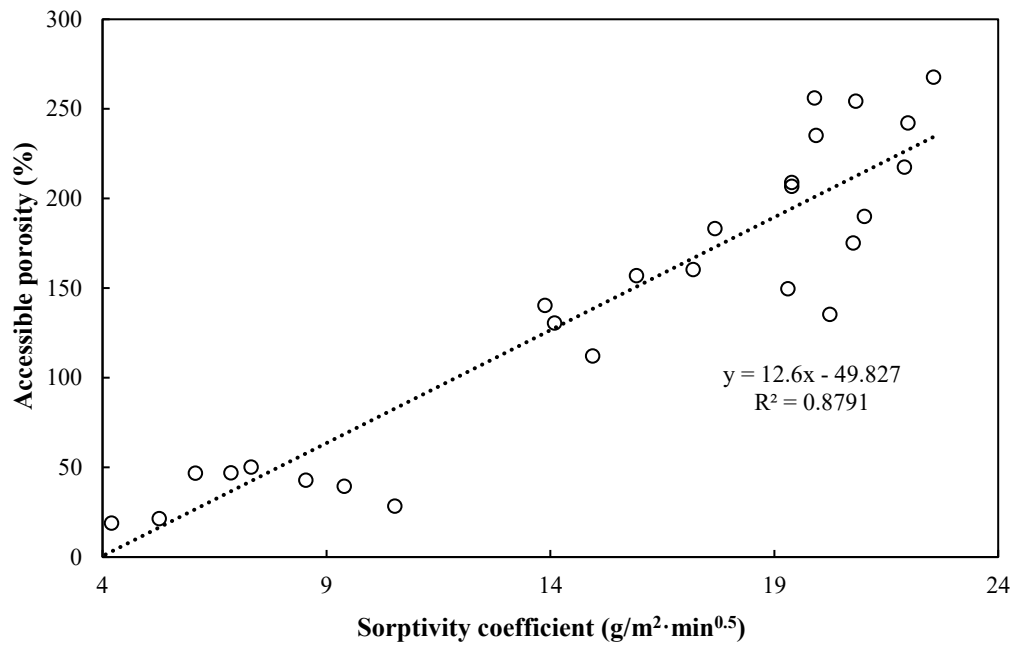


Figure 4.16 Correlation between sorptivity and accessible porosity

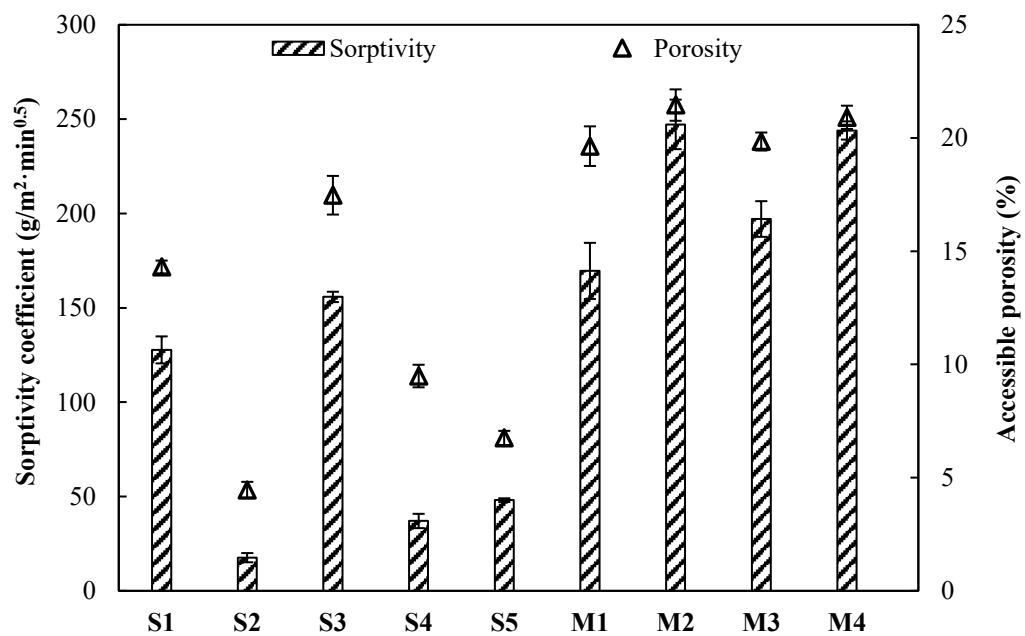


Figure 4.17 Sorptivity coefficient and accessible porosity

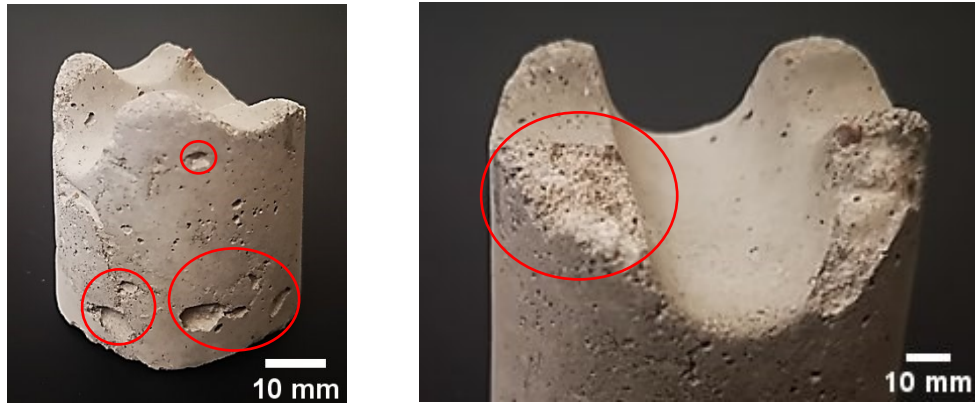


Figure 4.18 Typical M spacer showing surface defects such as large air voids caused by incomplete compaction, chips and fractures

Figure 4.19 shows typical cross-sections of spacers in the as-received condition and after accelerated carbonation, and application of phenolphthalein. It was surprising to see that S2, S4 and S5 were already carbonated to a significant extent in the as-received condition. The carbonated front was somewhat evenly distributed along the edges of each spacer including the edges of their tie holes. However, there are variations between replicates. For example, one of the three S2 replicates had an average carbonation depth of 1.6 mm, while the other two samples were non-carbonated. For S4 and S5, all three replicates were carbonated with an average depth of 2.5 and 2.8 mm respectively, with standard deviation of 0.7 and 1.1 mm respectively. The other spacer types showed no detectable carbonation. This suggests that variable amount of natural carbonation has occurred during the storage of these spacers. The amount of carbonation is likely to depend on the quality of the spacers, age and storage conditions. It is worth noting that spacer pre-carbonation and its effect on long-term durability of concrete structures has never been reported or studied before. It is likely that the pre-carbonation will affect the formation of passive layer where reinforcing steel is in contact with spacers. It is also expected that pre-carbonation will reduce the capacity to buffer subsequent carbonation and affect the concrete-spacer interfacial bonding. Therefore it is difficult to tell whether the carbonated spacer or the spacer-concrete interface are the most critical for predicting the carbonation front of concrete structures.

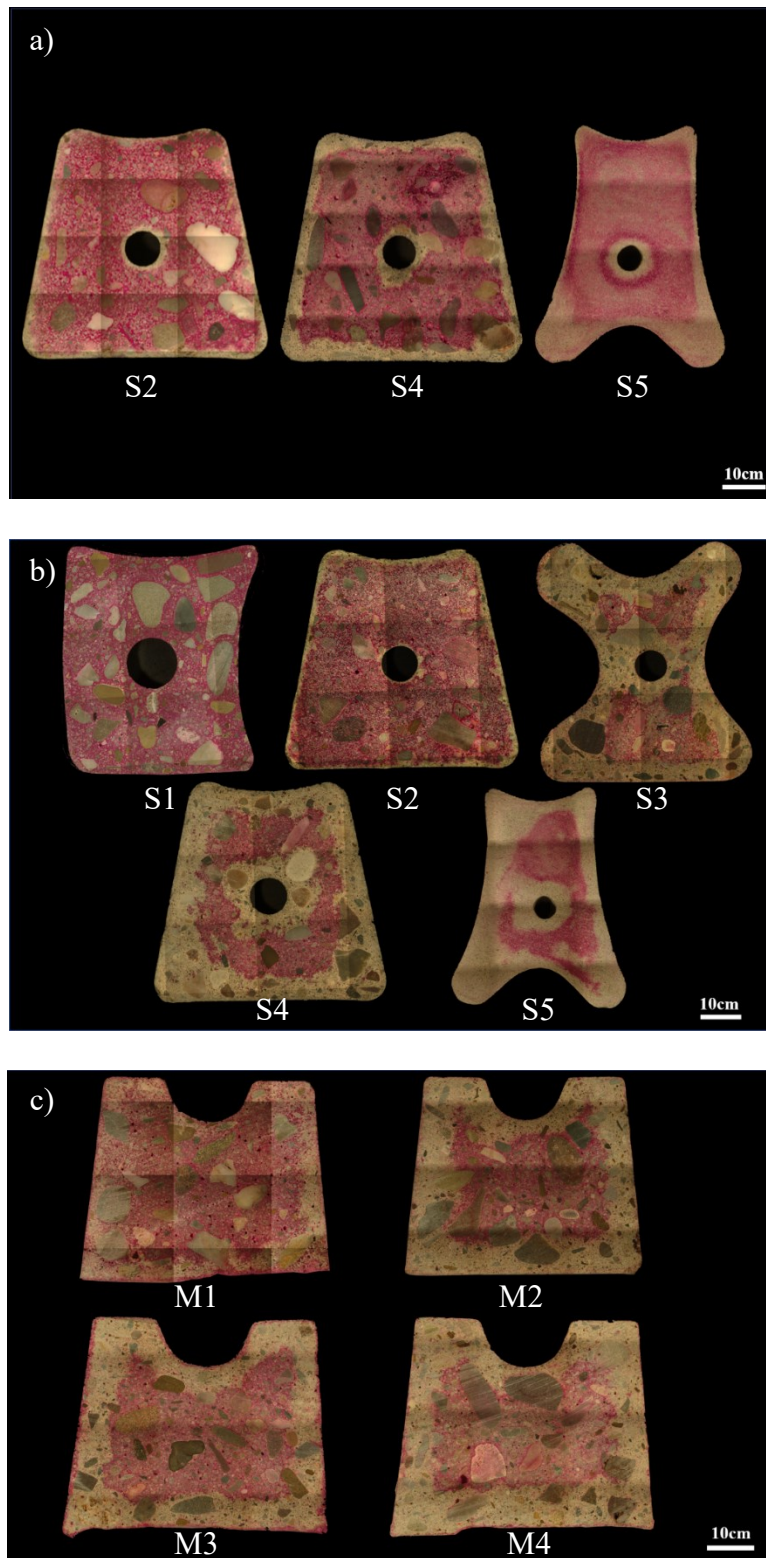


Figure 4.19 Cross sections of spacers showing the extent of carbonation in: a) S spacers (as-received); b) S spacers (after 28d accelerated carbonation); c) M spacers (after 28d accelerated carbonation)

Accelerated carbonation was conducted with the aim of comparing the carbonation resistance of different spacers. Carbonation depth was measured on 20 locations to quantify the carbonation extent in each S spacer sample. The results are shown in Figure 4.20a. A great variation was observed within each sample and between replicates. This might be related to the heterogeneity of the microstructure or the irregular shape of spacers, which resulted in highly different carbonation depths at different places. M spacers have similar cross-section sizes, but irregular cross-section shapes. Therefore, measurement of their carbonation depths was categorized into four regions as described in Chapter 4.2.5. Average carbonation depth at each region is shown in Figure 4.20b. The largest carbonation depth was found at top corners, followed by the sides, bottom and the top centre. Despite categorising the measurements into four regions, high standard deviations were still found between the results from the same region.

Subsequently, the carbonation area ratio, defined as the ratio of carbonation area to the cross-sectional area of each spacer, was measured with image analysis. Comparison between carbonation depth and carbonation area ratio is shown in Figure 4.21. As expected, the carbonation depth was positively correlated to the carbonation area ratio. The standard deviation for carbonation area ratio was much smaller than that of carbonation depth. However, an inverse trend between M spacers and S spacers was observed: the carbonation depths of M spacers were generally larger than those of S spacers, yet carbonation area ratios of M spacers were smaller than the respective S spacers. This is because of the larger cross-sectional areas of M spacers.

Figure 4.22 compares the original (in as-received condition) and accelerated carbonation depths. The accelerated carbonation depth ranged from 0 to 7.6 mm. S spacers (COV of 88.8%) showed higher variation than M spacers (COV of 51.8%), which could be a combined result of their differences in composition, quality and shape. However, limited research has been carried out on the carbonation resistance of cementitious spacers. Another interesting observation is that compared to S4 and S5, S2 spacers are more resistant to accelerated carbonation. This despite the fact that the S2 spacers were pre-carbonated. On the contrary, S3 spacers showed similar carbonation resistance to S4 and S5 spacers, yet no initial carbonation was observed. This is likely due to differences in age and storage conditions of the spacers.

There is some correlation between carbonation resistance, sorptivity coefficient and porosity, however the trend was not consistently observed. This shows that the spacers have different

mix composition (e.g. cement type and alkalinity) that influences carbonation resistance in addition to porosity.

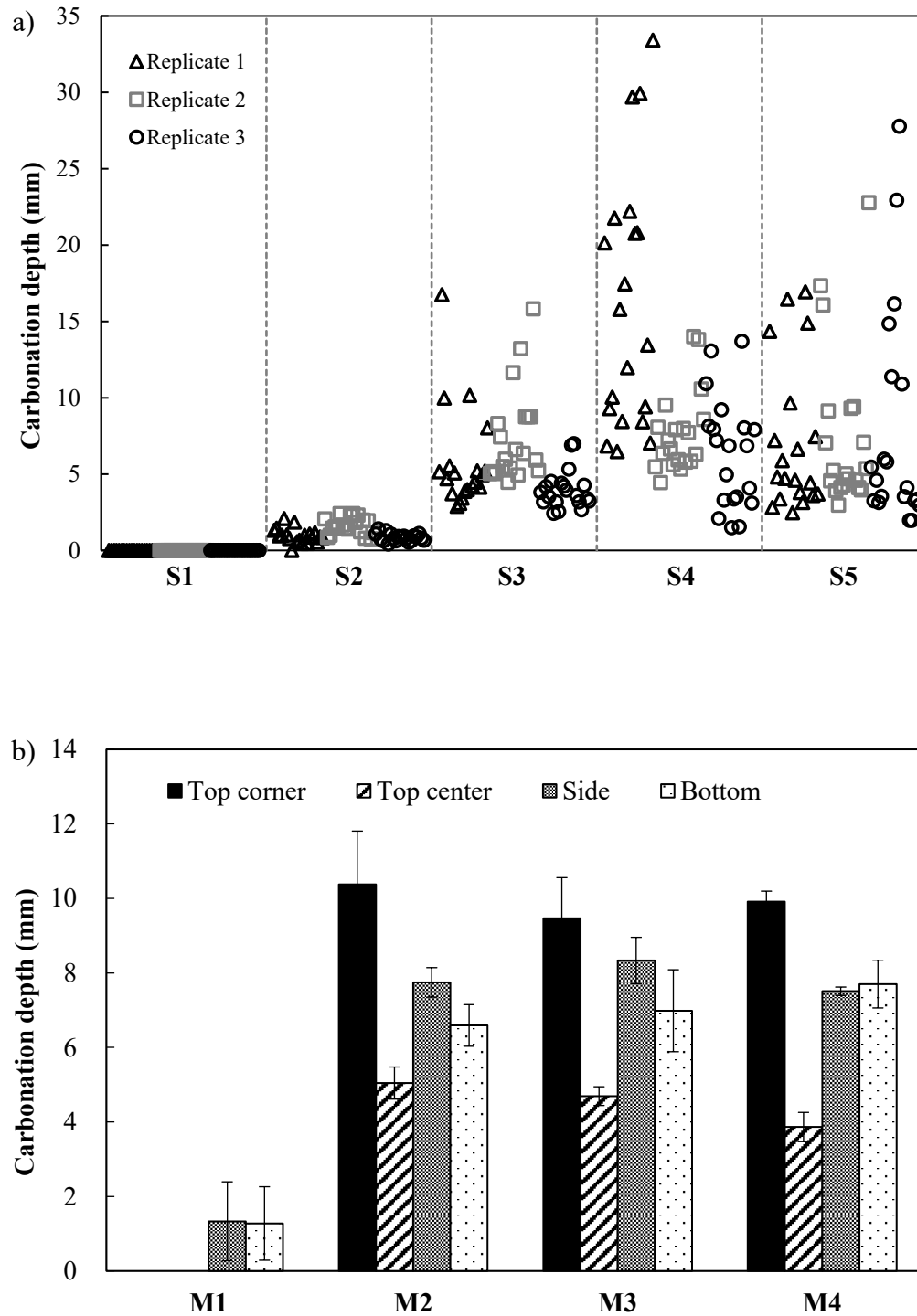


Figure 4.20 Accelerated carbonation depth results: a) S spacers; b) M spacers

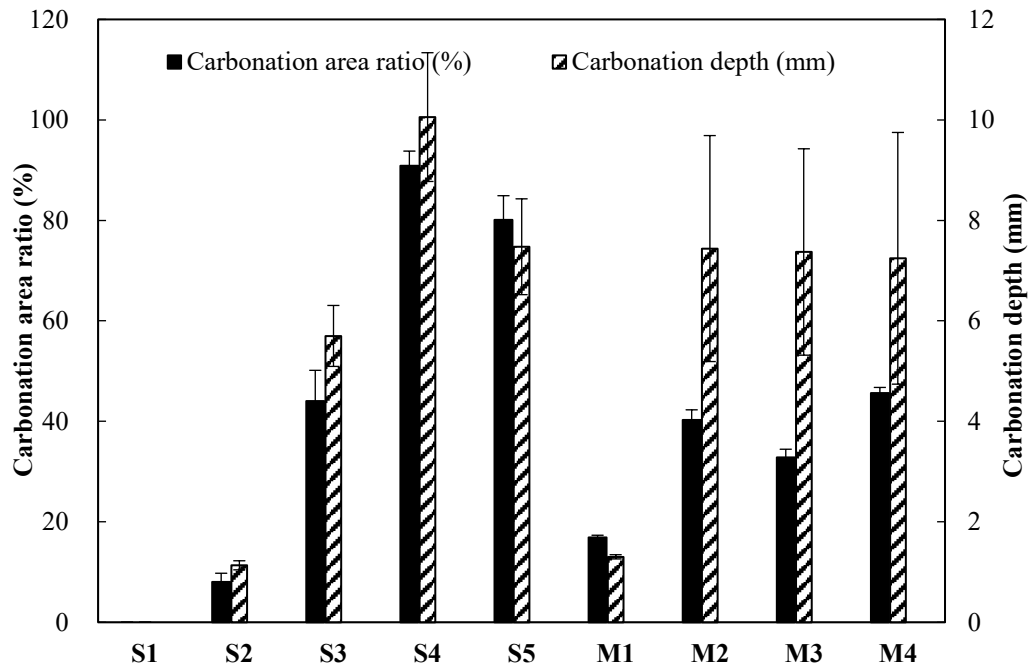


Figure 4.21 Comparison of accelerated carbonation depth and carbonation area ratio

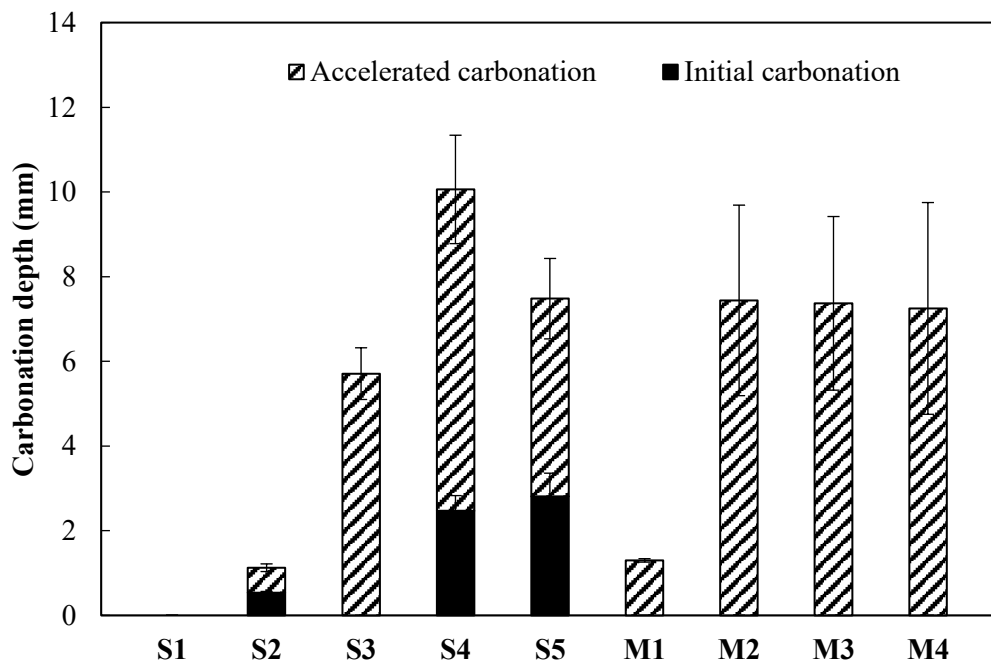


Figure 4.22 Initial and accelerated carbonation depths

4.3.4 Microstructure and image analysis

The mix components were analysed with SEM-BSE and EDS since there is a general lack of basic information on the composition of spacers. SEM-BSE images of typical samples are shown in Figure 4.23. Table 4.5 lists the detectable components. S5 spacers were the only type that contained GGBS and fibres, but without coarse aggregates. The fibres appeared as the dark coloured phase in the SEM-BSE image (shown in Figure 4.23a) which indicates they are non-metallic and are composed of light elements such as C, H and O. However, it is difficult to specify the fibre type due to lack of information. One possibility is that these are synthetic polymer fibres (e.g. polypropylene and polyethylene fibres) which are widely used in concrete for refining pore structure and reducing shrinkage. All the other spacers contained both fine and coarse aggregates. The maximum aggregate particle size was similar for these spacers (< 12 mm). However, their aggregate volume fraction and gradation could be different. The aggregate volume fraction of the tested spacers was found to range between 12.7% to 29.4%. As shown in Figure 4.24, S1 spacers had the highest aggregate volume fraction and largest aggregate size. This is suspected to be one of a major reason attributing to their high carbonation resistance because the incorporation of dense aggregate particles decreases the paste content and increases the tortuosity of pore structure, and thereby slowing down the rate of CO_2 ingress.

The volume fraction of anhydrous binders and pores are shown in Figure 4.24. Most spacers appear to be well cured and are well hydrated with only 1.2% to 4.0% anhydrous cement. The anhydrous binder volume fraction for S5 was significantly higher at 25.8%. This is due to the incorporation of GGBS, which accounted for 79.6% vol. of the anhydrous binder. It is well-known the GGBS reacts at a much slower rate compared to Portland cement. The relatively low anhydrous binder contents in the other spacers could also be due to the length of curing time, special curing conditions (e.g. steam curing or autoclaving), the use of rapid hardening cement or other reasons.

The volume fraction of the pores evaluated through image analysis included microcracks, which were observed in all tested spacers. Examples of microcracking are shown in Figure 4.25, which are likely to be drying-induced either prior to or during sample preparation for microscopy. Except for S2, the trends of measured porosity obtained from image analysis were generally in line with the results from vacuum saturation, with the image analysis value being approximately 15% (relative) lower. This is because large entrapped air voids are not measured

with image analysis, but included in the vacuum saturation porosity. For S2 spacers, the porosity from image analysis was unusually larger than the corresponding value from vacuum saturation. This could be an experimental error caused by disconnected pores in these spacers making them difficult to be detected through vacuum saturation.

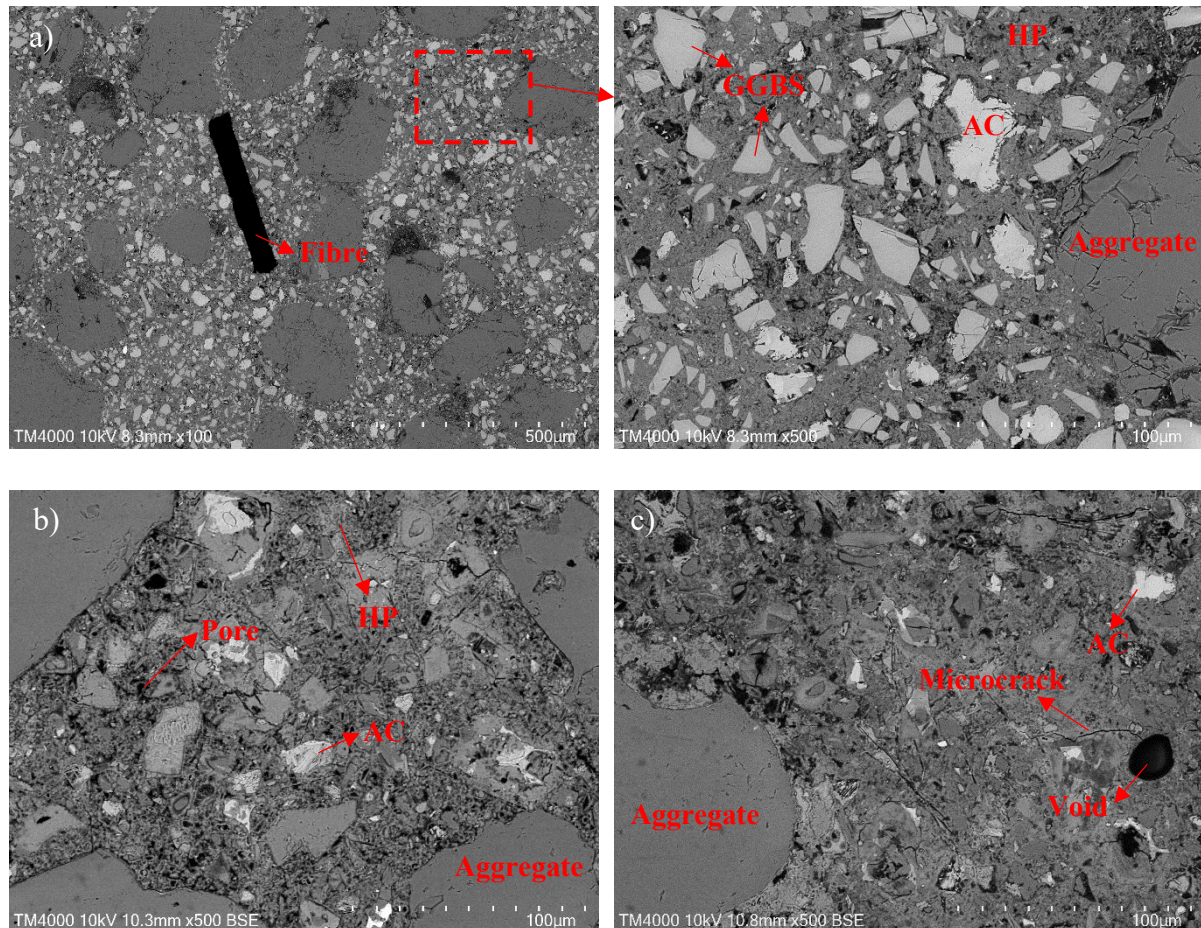


Figure 4.23 SEM-BSE images of typical samples of: a) S5; b) S3; c) M4 (AC and HP represent anhydrous cement and hydration products respectively)

Table 4.5 Composition of spacers detectable by SEM-BSE and EDS

Spacer	Portland cement	GGBS	Fine aggregate	Coarse aggregate	Fibre
S1	√		√	√(11.6)	
S2	√		√	√(8.4)	
S3	√		√	√(10.2)	
S4	√		√	√(8.2)	
S5	√	√	√(0.5)		√
M1	√		√	√(9.6)	
M2	√		√	√(8.8)	
M3	√		√	√(8.1)	
M4	√		√	√(9.4)	

Note: Detected components are marked with √; Maximum size of aggregates are listed in the brackets.

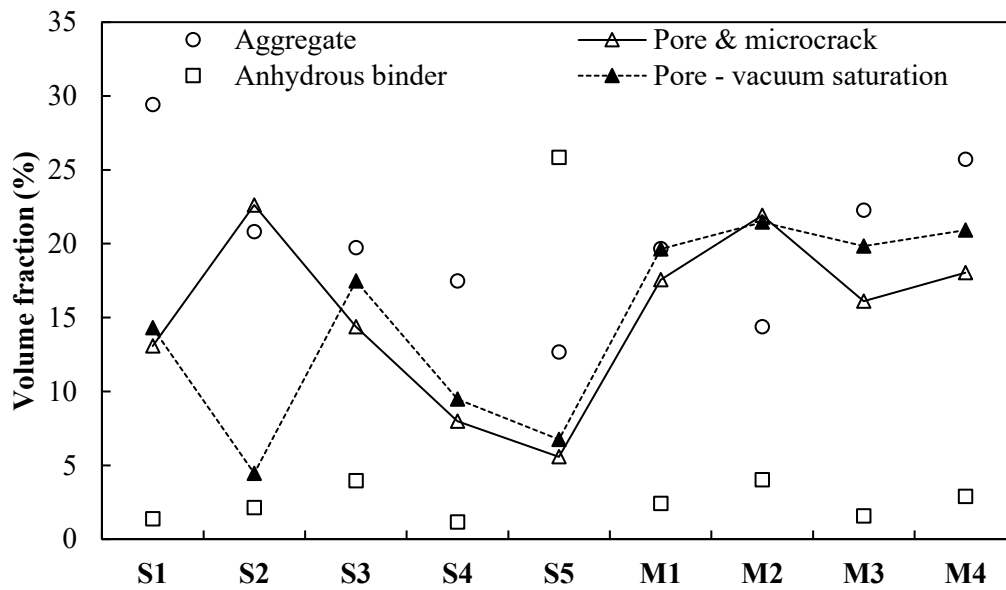


Figure 4.24 Volume fractions of aggregate, anhydrous binder, pore and microcrack

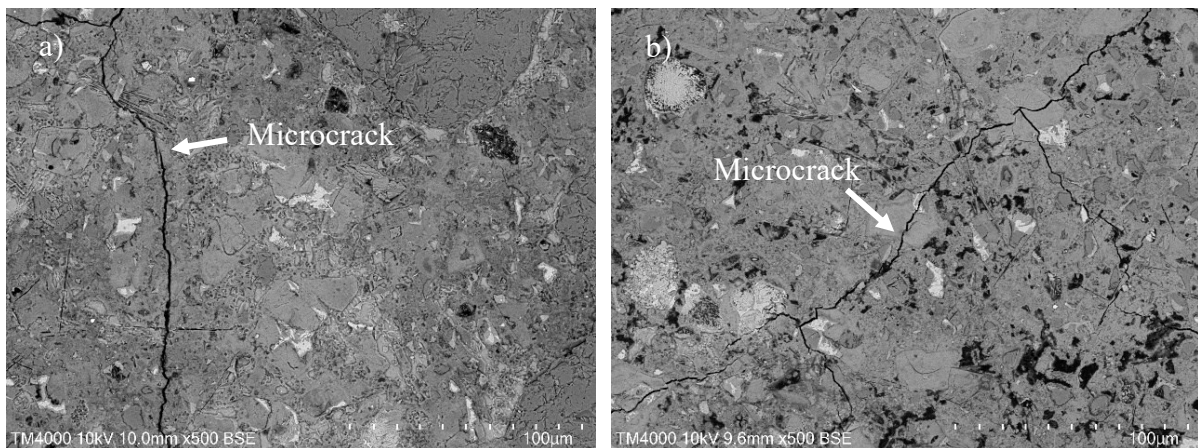


Figure 4.25 Typical microcracking observed in: a) S1 spacer and b) M1 spacer

4.3.5 Implications

This study has found huge variations in properties between different types of spacers. Properties that relate to durability (e.g. water sorptivity, accessible porosity and carbonation resistance) are more variable compared to dimensional or mechanical properties. This finding is perhaps not surprising because of the lack of attention given towards durability properties of spacers by the industry, compared to dimensional or mechanical properties. Indeed, national

standards (BS 7973-1:2001; BS 7973-2:2001, 2001) provide clear specifications on dimensional tolerance (e.g. cover shall be ± 1 mm for up to 75 mm and ± 2 mm for larger covers), and mechanical properties (e.g. compressive strength of cementitious spacers should not be less than 50 N/mm² at 28 days), see Table 2.1. Measurement and requirements on dimension and strength of spacers are well regulated. This is a huge contrast to durability related properties. Although some existing standards emphasise the importance of using materials with equivalent durability with concrete to manufacture spacers, there is a lack of detailed regulations on performance testing and reporting of their durability properties.

In practice, very few spacers' manufacturers provide technical information on the durability performance of their product. Selection of spacers in construction projects is commonly done based on cost and availability. Therefore, it is highly uncertain as to whether or not spacers used in construction achieve adequate durability, or at least an equivalent performance to the concrete in which spacers are used. Because spacers are used in large quantities in any concrete constructions and they are placed between reinforcement and the external environment, poor performing spacers would undoubtedly induce a weak zone for ingress of aggressive agents to access reinforcement and thereby reduce the efficiency of the protective concrete cover.

S spacers generally showed higher variation in properties compared to M spacers. Besides variations in mix composition, curing and storage conditions, the shape of spacers could be another reason affecting the properties of S spacers. For example, the bottom side of S spacers are in direct contact with the external environment and the exposed area is highly dependent on the shape of these spacers. A larger exposure area would potentially lead to greater detrimental effects. Additionally, the curvature of S spacers might impact the compaction of concrete around it and therefore the bonding between spacer and concrete. A highly porous spacer-concrete interface was observed with detrimental effects on mass transport properties (Alzyoud et al., 2016; Muslim et al., 2021b), which indicates the importance of spacer-concrete interface microstructure.

It is also worth noting the presence of tie wire hole in the middle of S spacers that is used for fixing reinforcing steel. The size of these tie holes is another variable (5 to 15 mm in this investigation) and sometimes changes with depth of the spacer. Compaction of concrete around the tie holes and in the presence of the tie wire has not been established. Poor compaction around this area could induce additional voidage at the spacer-concrete interface, increasing

the possibility of microcracking due to stress concentration when subjected to moisture and or thermal variations.

4.4 Conclusions

The properties and performance of cementitious spacers are expected to have major implications on the long-term durability of concrete structures, yet this is not well appreciated. In this chapter, the dimensional, mechanical, microstructure and durability properties of nine types of cementitious spacers from five different manufacturers were investigated. The spacers showed variations in shapes and sizes, and a large proportion (particularly the M spacers) had cover depths and compressive strengths that were outside of the acceptable tolerance range as defined by the British Standard (BS 7973-1:2001, 2001; BS 7973-2:2001, 2001). In addition, mechanical properties (e.g. compressive strength, modulus of rupture and dynamic Young's modulus) between different spacers showed clear variations. Compressive strength was positively correlated to the other mechanical properties irrespective of spacer type. Larger variations were observed for durability related properties (e.g. water sorptivity, carbonation resistance and porosity) compared to mechanical properties. This underscores the lack of industry regulation and guidance on the durability properties of spacers. Some spacers were already affected by carbonation in the as-received condition, suggesting low carbonation resistance of these materials and/or improper processing and storage conditions. The effects on spacer pre-carbonation on performance of concrete cover and embedded reinforcing steel remain unknown. The study also found variation in mix composition, microstructure and mass transport properties in the examined spacers. Some spacers were much less resistant to accelerated carbonation than others. Clearly, more work is needed to document the properties of cementitious spacers and understand their long-term impacts on concrete structures.

Chapter 5 Influence of cementitious spacers on mass transport properties of concrete

In this chapter, the influence of different cementitious spacers on concrete mass transport properties was investigated. Nine groups of cementitious spacers from five manufacturers were embedded in concrete with water/cement (w/c) ratios of 0.4 and 0.6. Samples were cured for 28d and conditioned at 50°C until constant weight. Oxygen diffusivity, oxygen permeability, water sorptivity and epoxy impregnation were evaluated. Results show that the incorporation of these spacers increased the mass transport properties of concrete to various levels. The increase is related to the microstructure of the spacer-concrete interface, properties of the spacer and its volume fraction. Fluorescent epoxy penetrated much deeper at the spacer-concrete interface compared to either the spacer or the bulk concrete, indicating that preferential transport paths occur at the interface.

5.1 Introduction

The inclusion of spacers has been found to increase the mass transport properties of concrete structures. According to Alzyoud et al. (2016), incorporating cementitious spacers of 50 mm height increase diffusivity, permeability and sorptivity by 57%, 107% and 19% respectively, for 28d cured concretes, even these were conditioned gently at 20°C, 75% RH. A more significant increase in these transport coefficients (of 87%, 96% and 25% respectively) was observed when concretes were conditioned at 50°C. Using SEM-BSE imaging, the authors observed a highly porous spacer-concrete interface with signs of debonding and microcracking, which was attributed as the main reason for the increase in transport properties. Similar observations were made by Muslim et al. (2021b) despite using supplementary cementitious materials (SCMs) to refine the microstructure of the spacer-concrete interface. It was also found that the interface provides an easy pathway for chloride and CO₂ to penetrate into concrete and reach the embedded reinforcement.

However, the afore-mentioned studies were carried out on one type of single cover cementitious spacer from a particular manufacturer. The effects of cementitious spacers on concrete durability could be dependent on both spacer-concrete interface and the properties of the spacer itself. The investigation from the previous chapter showed that a huge diversity exists in cementitious spacers that are currently used in the industry. Large variations were found in terms of the shape, composition, microstructure and durability properties.

Nevertheless, it is difficult to conclude whether these variations could lead to significant detrimental effects when the spacers are used in concrete structures. The direct impact introduced by the differences in properties between spacers and concrete could also be dependent on the size/volume of the spacers and bonding properties with concrete. The combined effects are likely to be complex, and this remains poorly understood. Therefore, a systematic study was conducted in this chapter, aiming at improving the understanding of the effects introduced by different cementitious spacers on the microstructure and durability of concrete.

5.2 Experimental

5.2.1 Materials and mix proportions

The nine groups of cementitious spacers investigated in Chapter 4 were further used in this chapter, as shown in Figure 5.1. Two concrete mixes with different w/c ratios were prepared. A mix with w/c ratio of 0.6 was selected to produce a low to moderate strength concrete. A second mix of 0.4 w/c ratio was prepared representing a normal strength concrete commonly used in the industry. Portland cement CEM I 52.5N was used as the main binder. Thames Valley gravel and sand with a maximum particle size of 10 mm and 5 mm respectively was used as the coarse and fine aggregates. Total volume fraction of aggregates was 70%, and sand to total aggregate volume ratio was 0.4. A superplasticizer (MasterGlenium SKY 1901) was used at 0.64% wt. of cement to achieve a good workability for the concrete mix with w/c ratio of 0.4. The concrete mix proportions were calculated according to the absolute volume method and these are shown in Table 5.1.

Table 5.1 Mix proportions of concrete

Mix ID	w/c ratio	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (L/m ³)	Superplasticizer (L/m ³)
C0.4	0.4	418.14	715.05	1073.64	175.06	2.66
C0.6	0.6	326.99	715.05	1073.64	205.85	0.00

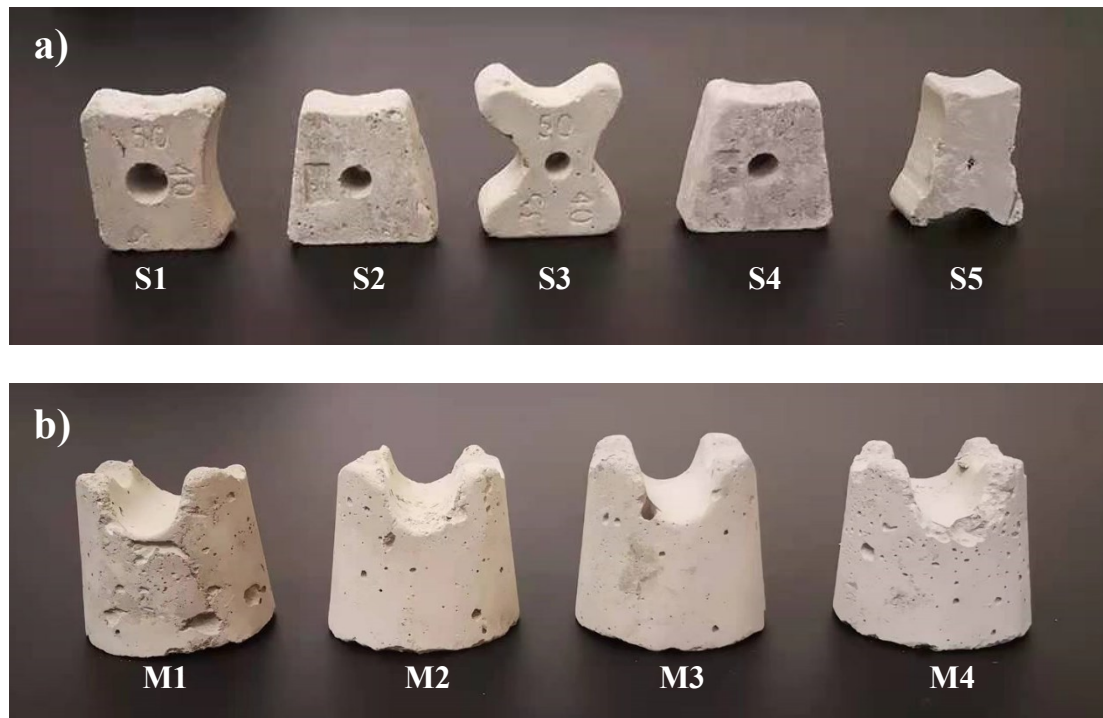


Figure 5.1 List of spacers

5.2.2 Sample preparation

Cylindrical samples with diameter of 100 mm and thickness of 50 mm were prepared for the mass transport property and epoxy impregnation tests. The prepared samples consist of either just the concrete as the control reference for comparison or spacer-concrete composite containing a single spacer embedded in the middle of the cylinder. The composite samples were cast in steel moulds using the set up shown in Figure 5.2. A thin layer of release agent (oil) was first applied on the internal curved surface of the cylindrical moulds. One spacer was then placed in the middle of each cylindrical mould and tightly secured by fixing a rebar against the spacer using wooden beams tightly screwed onto the base plate, as shown in Figure 5.2. The entire assembly was then vibrated on a vibrating table at the same intensity and duration, as used for concrete compaction. This was carried out to check that the spacers were well secured to the mould and that no relative displacements would occur during casting.

The concrete mix ingredients were batched by mass. Cement and aggregates were dry-mixed in a pan mixer for 30 seconds following by the addition of water (pre-mixed with superplasticizer) and a further wet mixing for 3 minutes. The freshly mixed concrete was then placed in the cylindrical mould in two equal layers and compacted by vibration. The cast

samples were surrounded with wet hessian and covered with plastic sheeting for the first 24 hours, then demoulded and cured in a fog room at 21°C, 100% RH for 28d. The top surface of the cast cylindrical samples tend to be uneven due to cementitious spacers protruding out, or the imprint left by the rebar used to secure the spacers, as shown in Figure 5.3a. The uneven surface could cause difficulties during mass transport testing or induce biases in the test results. Therefore, a thin layer was trimmed off using a diamond blade to flatten the top surface (Figure 5.3b). The samples were then transferred for conditioning.

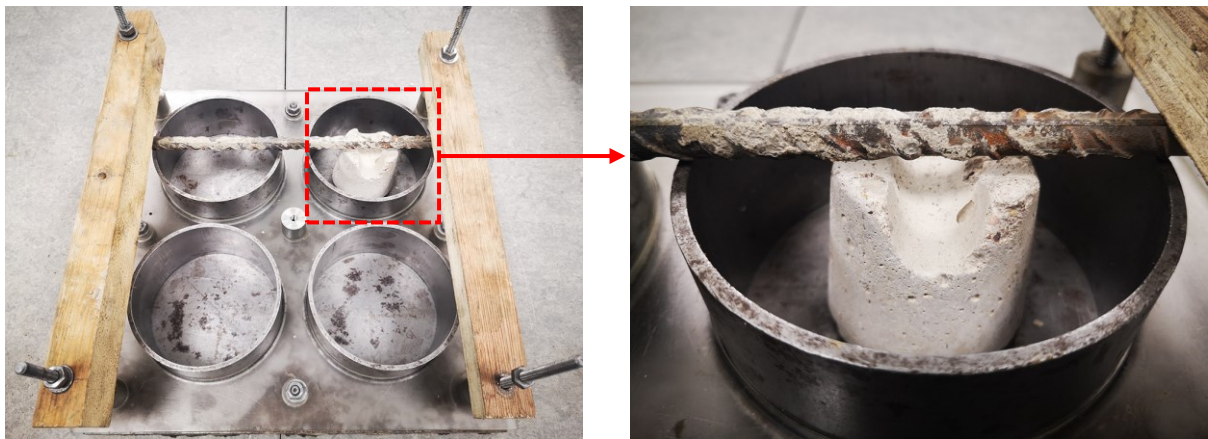


Figure 5.2 Setup for sample casting

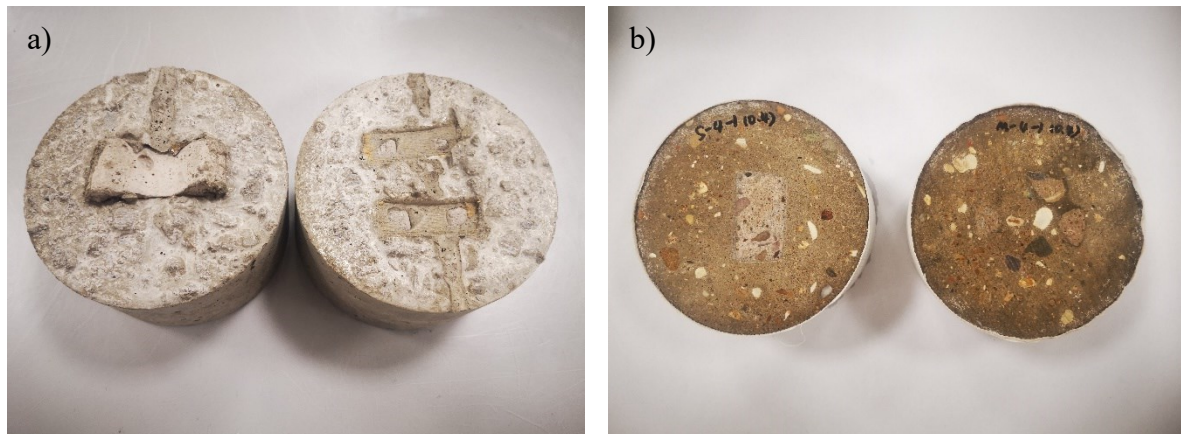


Figure 5.3 Top surface of typical samples: a) as cast; b) after trimming and finishing.

5.2.3 Mass transport and epoxy impregnation

Prior to testing, all samples were conditioned by drying to constant weight in an oven at 50°C. This typically required 8-12 weeks to reach a steady-state mass. The samples were then cooled

to room temperature in a desiccator right before the tests. Three replicate samples were tested following the sequence of oxygen diffusivity and oxygen permeability. Then two of the replicates were used for water sorptivity testing, and the remaining sample was used for epoxy impregnation under pressure. Test procedures are described in Chapters 3.4 and 3.5. It is worth mentioning that the sorptivity coefficients were determined using the water absorption measurements during the first 6.5 hours of the test.

5.3 Results and discussion

5.3.1 Mass transport properties

The average mass transport results are listed in Table 5.2. Note that sample designation is based on the reference concrete and type of embedded spacers. For example, C0.4-S1 refers to samples with S1 spacers embedded in C0.4 concrete, and C0.4-N refers to the control sample of C0.4 concrete with no spacers. Comparative results from Alzyoud et al. (2016) was also included, and these were from samples of same curing, conditioning and testing regimes. A different type of S spacer (also with the cover depth of 50 mm and shown in Figure 5.4) manufactured by Max Frank GmbH was embedded in concrete with the same mix as C0.4. Therefore the sample is designated as C0.4-Alz. Compared to C0.4-Alz, most samples from this project had higher mass transport properties (6 for diffusivity, 9 for permeability and 3 for sorptivity). This again underscores the variability in the properties of spacers as discussed in the previous chapter.

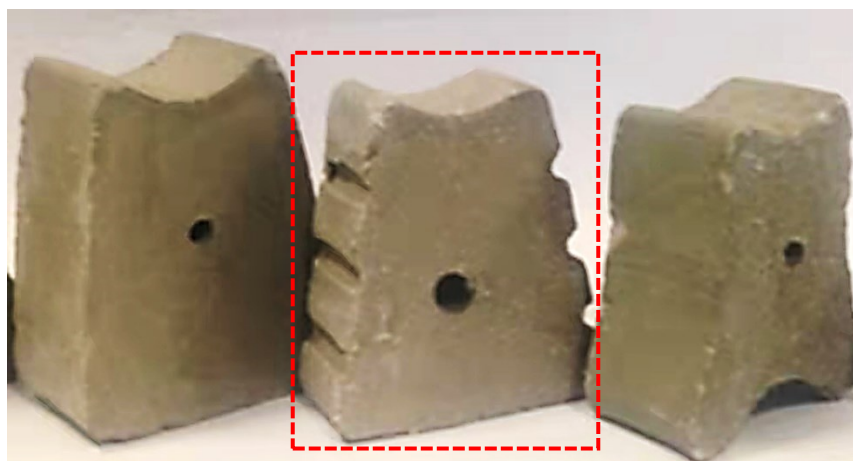


Figure 5.4 S spacer (marked in red) used by Alzyoud et al. (2016)

As expected, the transport properties of all samples with w/c ratio of 0.6 were consistently higher than the corresponding values for samples with w/c ratio of 0.4. This shows that the test methods were able to detect changes in mass transport caused by the increase in porosity with w/c ratio. For samples with w/c ratio of 0.6, the highest diffusivity and sorptivity coefficients were 2.6 and 1.4 times the lowest value (from control sample), ranging from 13.2×10^{-8} to $34.4 \times 10^{-8} \text{ m}^2/\text{s}$ and 145.1 to $202.2 \text{ g/m}^2\text{min}^{0.5}$ respectively. Permeability was found to have a higher maximum to minimum ratio of 15.0, ranging from 23.9×10^{-17} to $359.4 \times 10^{-17} \text{ m}^2$. For samples with w/c ratio of 0.4, the highest diffusivity and sorptivity coefficients were 2.1 and 2.8 times the lowest value, ranging from 5.8×10^{-8} to $12.2 \times 10^{-8} \text{ m}^2/\text{s}$ and 43.0 to $120.0 \text{ g/m}^2\text{min}^{0.5}$ respectively. Permeability was also found to have the highest maximum to minimum ratio of 30.8, ranging from 7.7×10^{-17} to $235.6 \times 10^{-17} \text{ m}^2$.

Table 5.2 Results of mass transport property

Sample ID	Diffusivity ($\times 10^{-8} \text{ m}^2/\text{s}$)	Permeability ($\times 10^{-17} \text{ m}^2$)	Sorptivity ($\text{g/m}^2\text{min}^{0.5}$)	Sample ID	Diffusivity ($\times 10^{-8} \text{ m}^2/\text{s}$)	Permeability ($\times 10^{-17} \text{ m}^2$)	Sorptivity ($\text{g/m}^2\text{min}^{0.5}$)
C0.6-N	13.2 (0.2)	23.9 (0.2)	145.1 (2.1)	C0.4-N	5.8 (0.01)	7.7 (0.0)	43.0 (0.2)
C0.6-S1	19.2 (0.2)	93.7 (0.6)	156.3 (5.1)	C0.4-S1	8.8 (0.1)	67.7 (0.7)	65.9 (1.1)
C0.6-S2	18.1 (0.4)	38.5 (0.3)	171 (5.7)	C0.4-S2	10.8 (0.3)	11.1 (0.4)	60.8 (6.0)
C0.6-S3	20.4 (0.7)	359.4 (9.0)	183.7 (9.4)	C0.4-S3	10.9 (1.6)	235.6 (2.2)	84.7 (1.0)
C0.6-S4	19.1 (0.3)	72.3 (0.8)	155.4 (2.7)	C0.4-S4	9.0 (0.3)	22.3 (0.3)	63.9 (3.4)
C0.6-S5	19.4 (0.6)	81.8 (0.6)	192.9 (3.9)	C0.4-S5	10.3 (0.2)	38.2 (0.2)	69.3 (0.4)
C0.6-M1	19.6 (0.4)	175.2 (6.7)	165.8 (0.7)	C0.4-M1	11.1 (0.8)	77.1 (1.1)	77.0 (4.0)
C0.6-M2	34.4 (0.6)	222.7 (1.4)	181.4 (2.6)	C0.4-M2	11.9 (0.3)	117.0 (0.9)	114.5 (3.7)
C0.6-M3	21.0 (0.3)	94.6 (1.0)	190.2 (2.8)	C0.4-M3	12.2 (0.4)	54.5 (0.4)	103.3 (1.3)
C0.6-M4	18.3 (0.1)	138.3 (2.0)	202.2 (14.2)	C0.4-M4	11.7 (0.4)	110.4 (1.5)	120.0 (5.9)
				C0.4-Alz*	10.5 (1.4)	9.5 (0.5)	86.0 (1.8)

Note: Standard deviation is indicated in brackets; * comes from Alzyoud et al. (2016).

The incorporation of cementitious spacers consistently led to an increase in mass transport properties regardless of the type of spacer and the w/c ratio of concrete. To better understand the effects induced by spacers, the transport coefficients of samples with embedded spacers were normalised to the values of the respective control samples without spacers, as shown in Figure 5.5. For samples with w/c ratio of 0.6, the normalised diffusivity, permeability, and sorptivity ranged from 1.4 to 2.6, 1.6 to 15.0, and 1.1 to 1.4 respectively. For samples with w/c ratio of 0.4, the corresponding ranges were 1.2 to 2.1, 1.2 to 30.8, and 1.4 to 2.8 respectively. Permeability was affected the most by the incorporation of cementitious spacers. This coincides with the findings from Alzyoud et al. (2016) and Muslim et al. (2021b). The coefficient of variation (COV) of the normalised diffusivity, permeability, and sorptivity were 24.3%, 69.9% and 9.3% for samples with w/c ratio of 0.6, and 11.2%, 83.5% and 27.0% for samples with w/c ratio of 0.4. Therefore, the effects on permeability induced by spacers were also observed with the highest variations.

Samples with w/c ratio of 0.4 showed higher normalised transport values than those with w/c ratio of 0.6. This indicates that a more pronounced increase in mass transport was induced by the spacers when embedded in concrete with low w/c ratio. Concrete with lower w/c ratio have denser microstructure and therefore is likely to be more sensitive to the disruption induced by spacers. Additionally, concrete with low w/c ratio tends to have higher drying and autogenous shrinkage (Yio et al., 2021; Wu et al., 2017; Zhang et al., 2003). The presence of spacers would act as an internal restraint to the shrinkage. This induces stress concentrations at the spacer-concrete interface, generating microcracks and increasing the local mass transport properties. It is known that the effect of microcracking on mass transport properties, in particular permeability, is greater on denser (low w/c ratio) systems compared to more porous systems (Abyaneh et al., 2013; Wu et al., 2014). However, the normalised transport coefficients showed inconsistent trends with type of spacers when embedded in concrete with different w/c ratios. This might be related to the variation in the properties of the spacer used (Chapter 4), the characteristics of the spacer-concrete interface, and effects induced by the compaction of concrete or the drying process.

Figure 5.6 shows the percentage change of mass transport properties induced by spacers compared to the control samples, plotted in the form of a frequency distribution diagram. Results from 72 samples of each w/c ratio were analysed, with a percentage increase ranging from 3% to 1466% and 22% to 3026% for w/c ratio of 0.6 and 0.4 respectively. The majority

data lie between 10% to 1000% regardless of the w/c ratio. However, more samples at w/c ratio of 0.4 gave increases greater than 100% compared to samples at w/c ratio of 0.6.

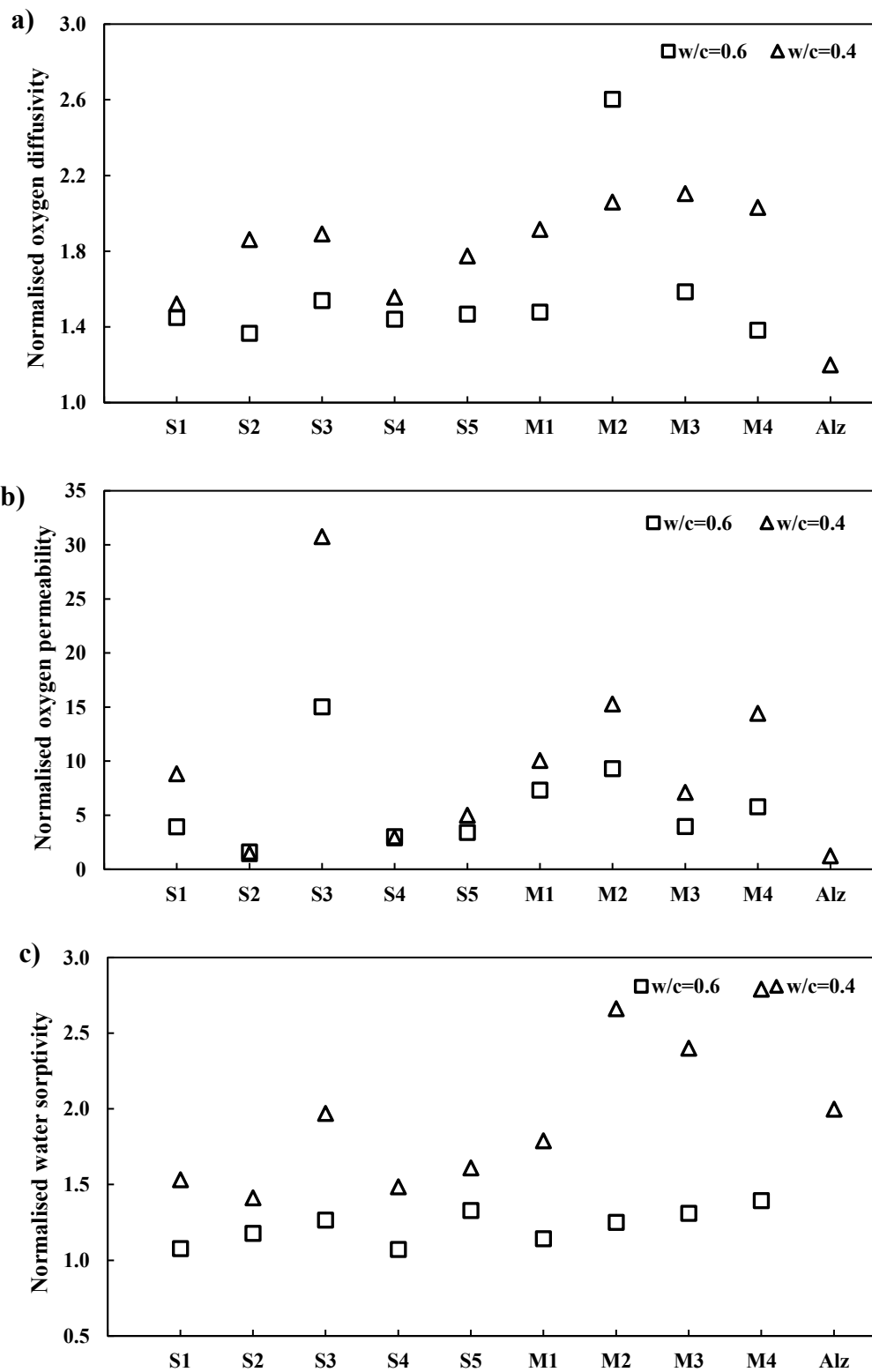


Figure 5.5 Effect of spacers on mass transport: a) O₂ diffusivity; b) O₂ permeability; c) water sorptivity. The results are normalised to the respective control reference sample.

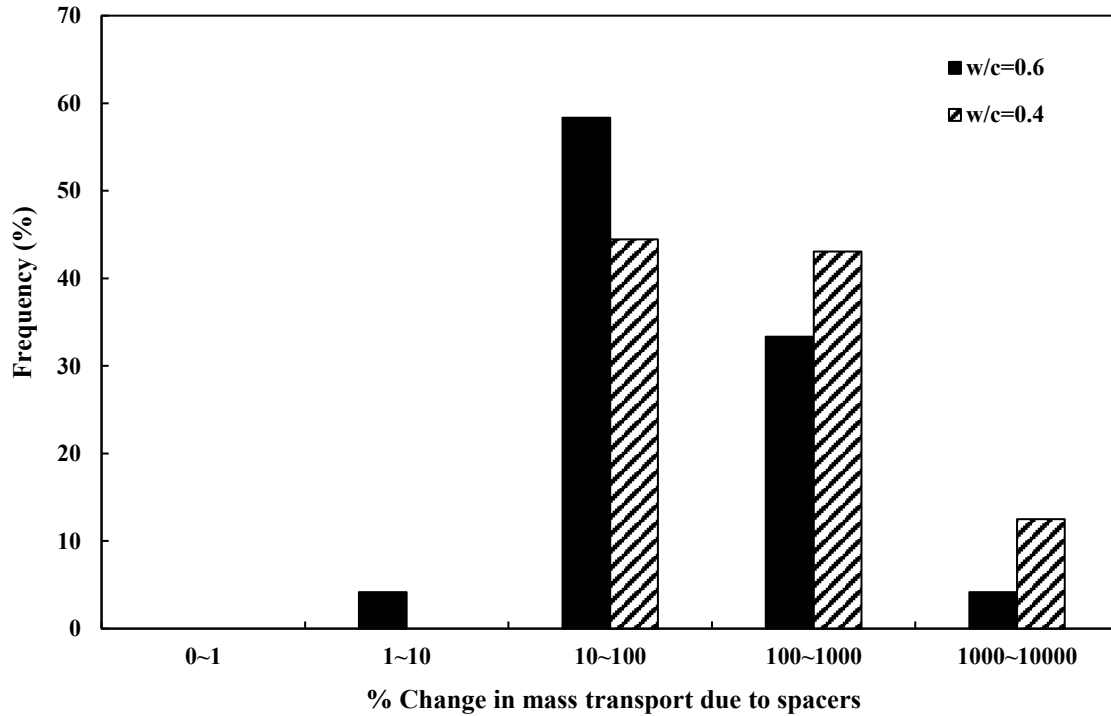


Figure 5.6 Frequency distribution of percentage change in mass transport induced by spacers

5.3.2 Correlation between spacer and spacer-concrete composite sample

Figure 5.7 shows the sorptivity of spacers and spacer-concrete composites, benchmarked against the sorptivity of concrete reference sample at w/c ratio of 0.6 and 0.4. The data shows a wide range of sorptivity values among the tested spacers, with 6 sets having higher sorptivity than the reference concrete at 0.6 w/c ratio, and only 2 sets having lower values than the reference concrete at 0.4 w/c ratio. However, all composite samples gave higher sorptivity than the respective reference concrete, despite some spacers having remarkably low sorptivity values (e.g. S2, S4). This indicates the significant detrimental impacts induced by the spacer-concrete interface, which is consistent with previous investigations (Alzyoud et al., 2016; Muslim et al., 2021b).

It was also observed that in some cases, the sorptivity of composite samples ranged in between of the values of the respective spacers and reference concrete. This despite the fact that some spacers have remarkably higher sorptivity than the respective reference concrete. One example of this is the composite samples embedded with M spacers. This could be due to the relatively

small volume fraction of these spacers compensating their effects on the sorptivity of the composite samples.

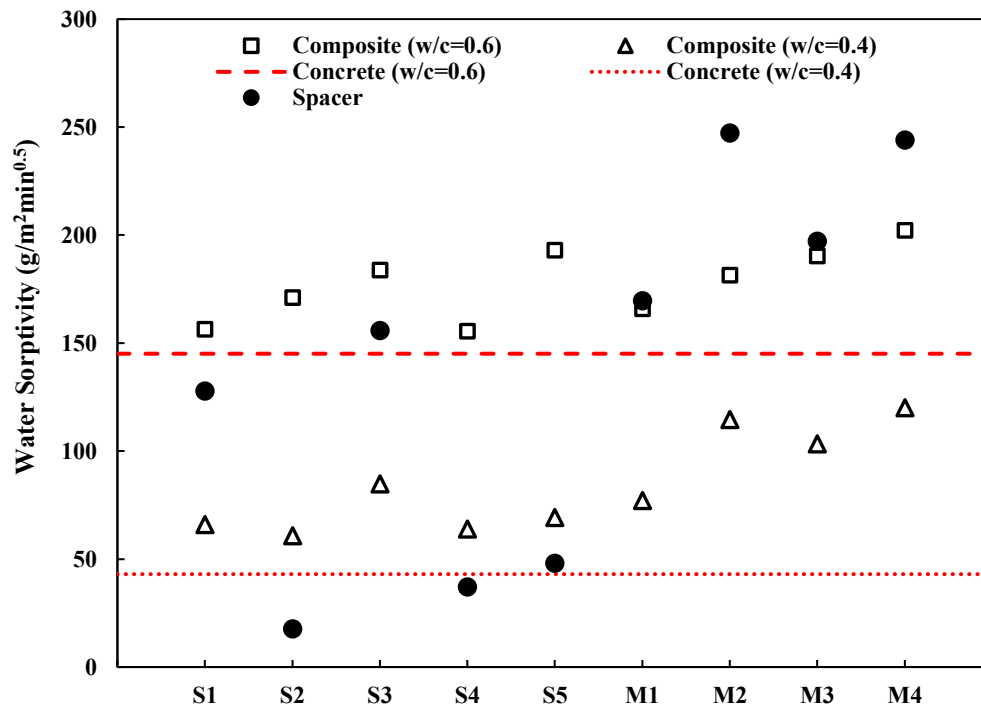


Figure 5.7 Sorptivity of spacer and spacer-concrete composites

Correlation between the sorptivity of the spacer and spacer-concrete composites is shown in Figure 5.8. A strong correlation was observed between the sorptivity of spacer and composite samples with 0.4 w/c ratio concrete. However, for samples with 0.6 w/c ratio concrete, the correlation was much weaker. This indicates that the sorptivity of spacers could highly affect the water absorption of concrete structures, particularly when using denser concrete with low w/c ratio. For samples with high w/c ratio concrete however, water absorption mainly occurred through the highly porous bulk concrete and spacer-concrete interface, rather than through the spacer itself and therefore the properties of the spacer become less critical.

Figure 5.9 plots the mass transport properties of spacer-concrete composites against the porosity of corresponding spacers. Clearly scattered points (marked in red) were excluded from the regression. Permeability of the composite samples showed stronger correlation with spacer porosity than diffusivity and sorptivity. This indicates the remarkable effects on concrete gas permeation by spacer porosity. It also gives one possible reason for permeability being the most negatively affected mass transport property by spacer inclusion.

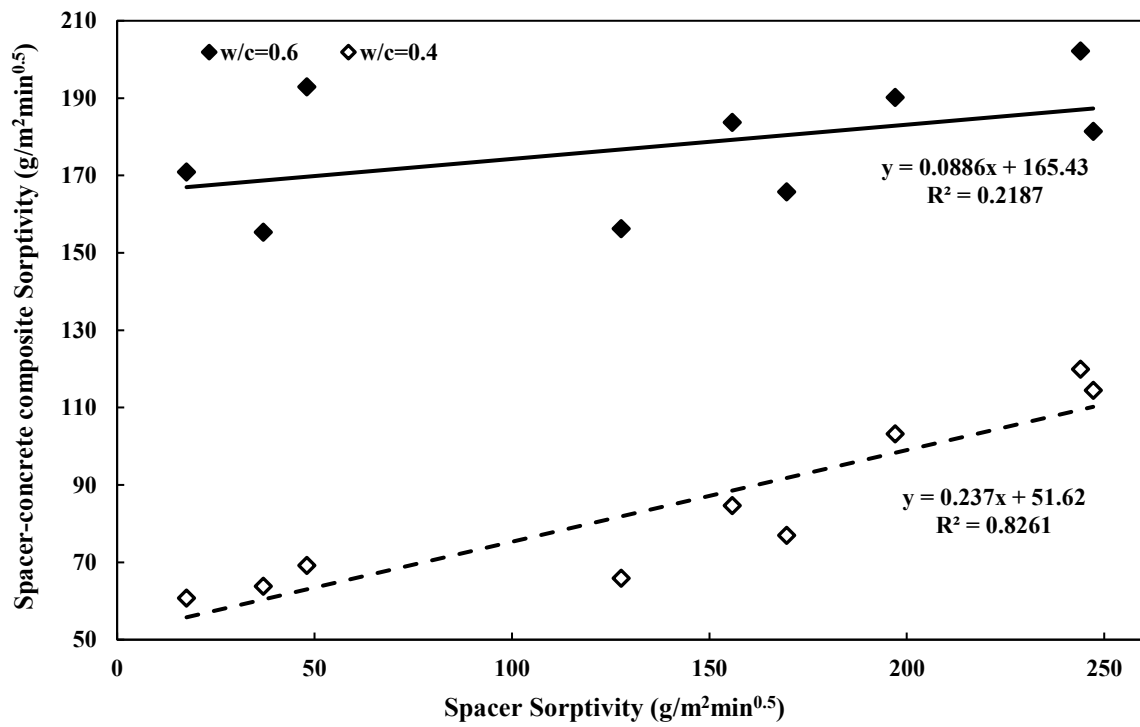
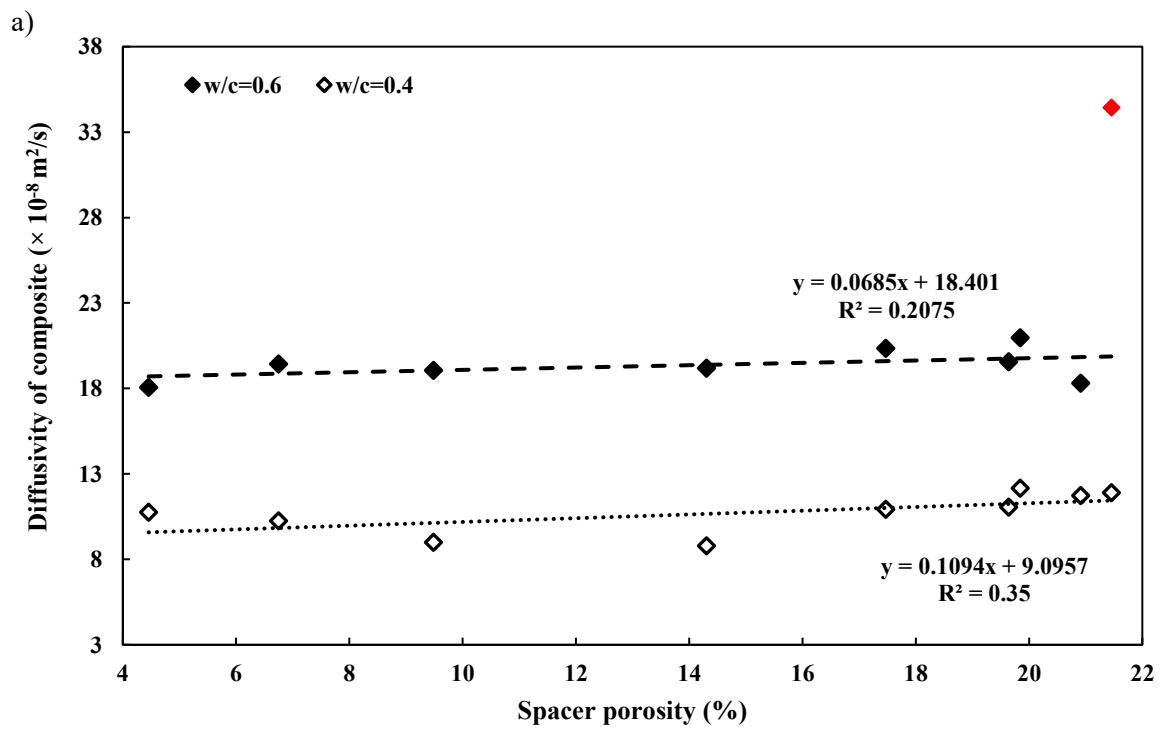


Figure 5.8 Correlation between the sorptivity of spacers and spacer-concrete composites



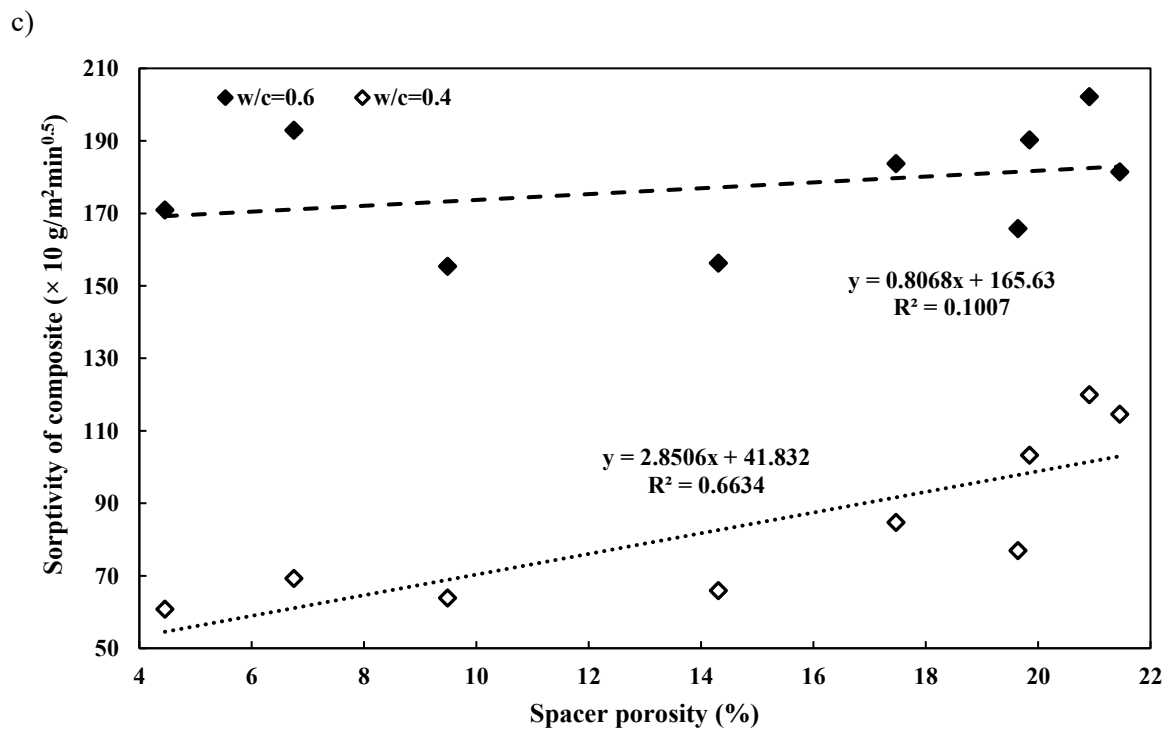
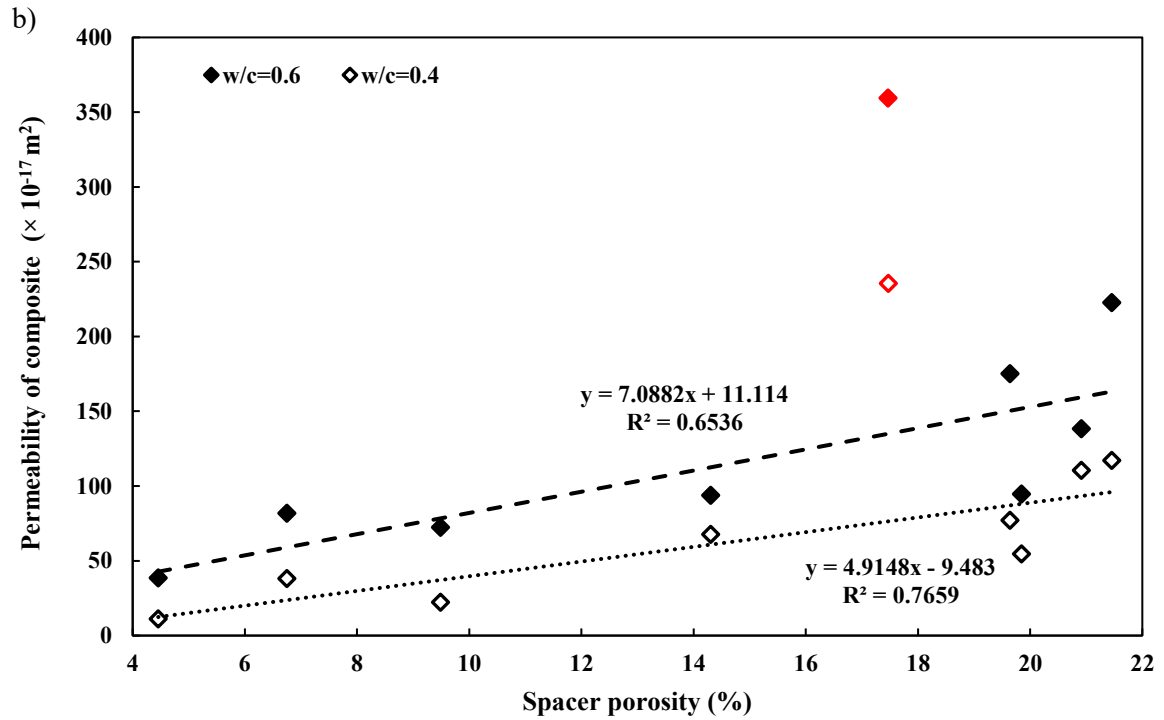


Figure 5.9 Correlation between the spacer porosity and mass transport properties of spacer-concrete composites e.g.: a) diffusivity; b) permeability; c) sorptivity

5.3.3 Fluorescent epoxy impregnation

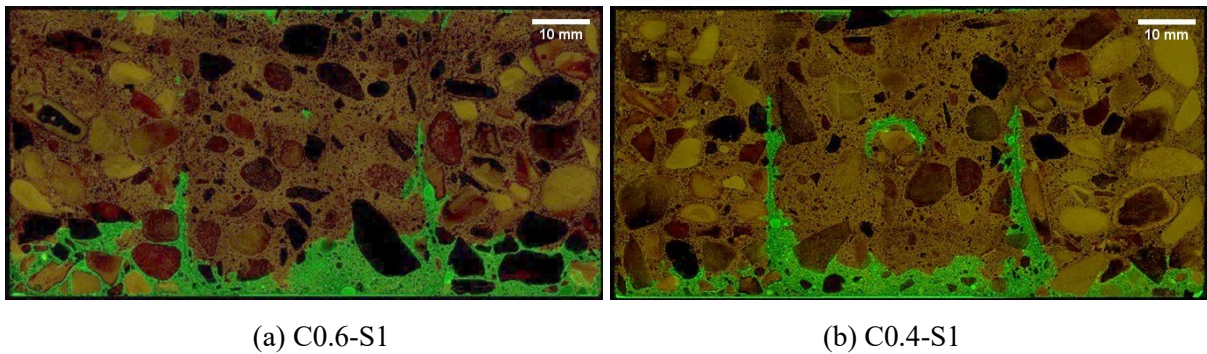
Penetration of the fluorescent epoxy into spacer-concrete composite samples (from the bottom face) under pressure is shown in Figure 5.10. The epoxy penetration into 0.6 w/c ratio concrete was consistently greater than that of the 0.4 w/c ratio concrete, as expected. A clear penetration of the epoxy could be observed alongside the spacer-concrete interface, which were much deeper than the impregnation into the spacer or the concrete itself. This provides strong evidence that the spacer-concrete interface is inherently weak, porous and microcracked, offering consistently low resistance to mass transport.

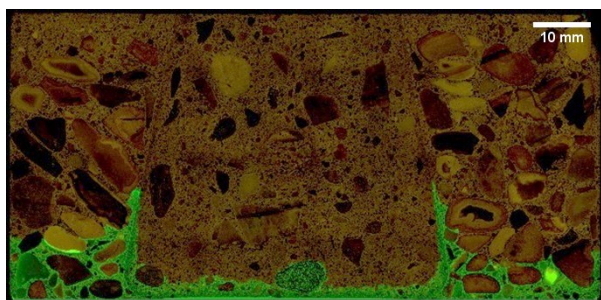
However, variation in the impregnation depth could be seen between spacers. Some spacers performed worse than others, which indicate differences in bonding between spacer and concrete. It is worth noting that the images show the mass transport phenomenon on one cross-section through the centre of each sample, and it is possible that a cross-section taken from another location display a slightly different impregnation pattern. An evidence of this is that in images (b), (e) and (f), a clear fluorescence pattern could be seen around the tie hole in the spacer, yet these patterns were not connected to the bottom face or the spacer-concrete interface. This shows that the microcracks inherent in spacers (discussed in Chapter 4.2.6) offer another pathway for epoxy penetration. Another indication is the difficulty of compacting concrete into the tie hole of S spacers. This could reduce the bonding efficiency between spacer and concrete. Furthermore, it could add an extra pathway for aggressive species to pass into concrete when microcracks are generate around it, as shown in image (j).

For samples with S5 spacer, the epoxy impregnation into the concrete occurred between the legs of the spacer on the bottom side. The designed shape on the bottom side of S5 spacers is beneficial in terms of aesthetics because the spacer would be embedded and hidden from view. However, it might lead to difficulties in placing and compacting concrete into the nestled space between the bottom legs of these spacers, especially when using large aggregates. This could lead to a loss of protection efficiency provided by concrete cover. Indeed, large voidage due to entrapped air can be seen on the underside of S5 spacer and all the M spacers, which is subsequently filled with fluorescent epoxy. The worse situation could be seen in image (p), where the M3 spacer appears inclined with a large gap on the bottom side. This is attributed to the uneven bottom surface of M spacers as shown in Figure 5.11. In addition to the loss of efficient cover, it is also suspected if these spacers could lead to stability issues when fixed to the formwork during construction.

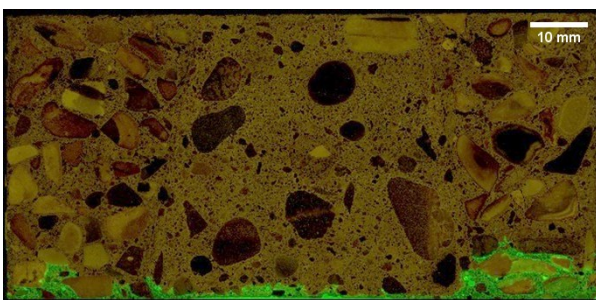
The maximum impregnation depth through the spacer, concrete and their interface (D_s , D_c and D_{IT}) and thickness (T) of each sample was measured through image analysis, as shown in Table 5.3. Most samples showed slightly higher impregnation depth into concrete than spacers. This is due to the higher porosity of the concrete and higher aggregate volume fraction in the concrete, which increases pore connectivity through the ITZ. However, for samples with 0.4 w/c ratio concrete, higher impregnation depth was observed in S5 and M spacers. It could be attributed to the microcracking inherent in spacers (S5) or their obviously higher porosity (M spacers, shown in Figure 4.14) relative to the concrete. The inclusion of such spacers will undoubtedly reduce the efficiency of concrete cover and should be avoided. Yet, this is difficult to implement due to a lack of standardised tests for quantifying the durability of spacers.

D_{IT}/T ratio was calculated as an index comparing the maximum impregnation depth through the entire samples. No consistent trends for D_{IT}/T could be observed with w/c ratio or the type of spacer used. However, 15 out of the 18 samples ($> 83\%$) had a D_{IT}/T ratio larger than 50%. Half of the samples showed complete impregnation through spacer-concrete interface, which indicates poor bonding between the spacers and concrete. S2 spacer showed the best bonding with concrete despite the w/c ratio, which is also correspondent with its low mass transport properties. However, not all samples showed consistent trends between the impregnation depth and mass transport. For example, C0.6-S4 showed small mass transport but was completely impregnated through the spacer-concrete interface. This could be related to different mechanisms occurring during mass transport testing and epoxy impregnation. Another possible reason could be the high sensitivity of the spacer-concrete interface to the applied pressure during epoxy impregnation.

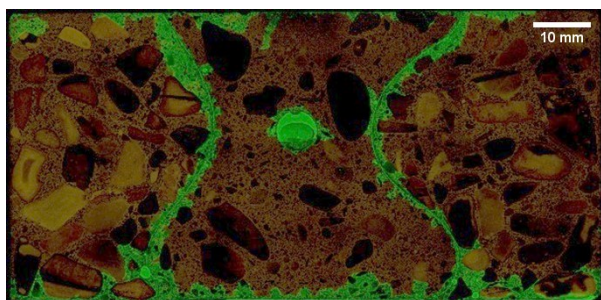




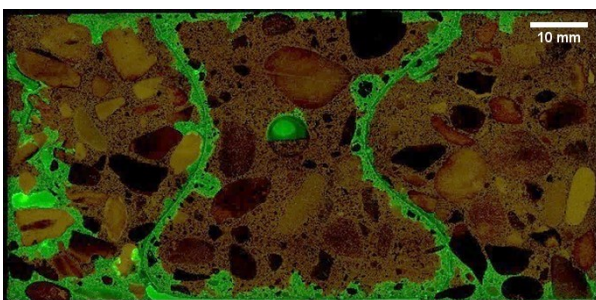
(c) C0.6-S2



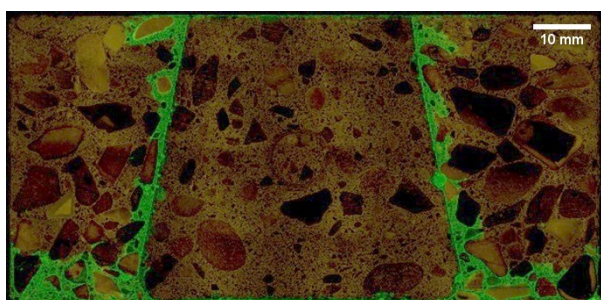
(d) C0.4-S2



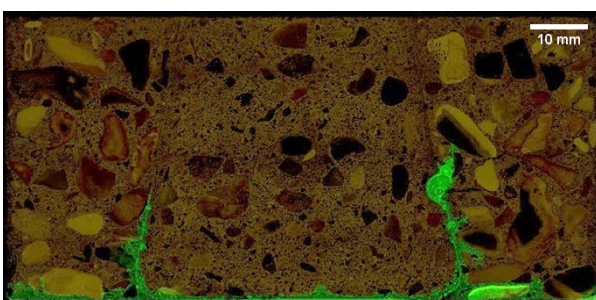
(e) C0.6-S3



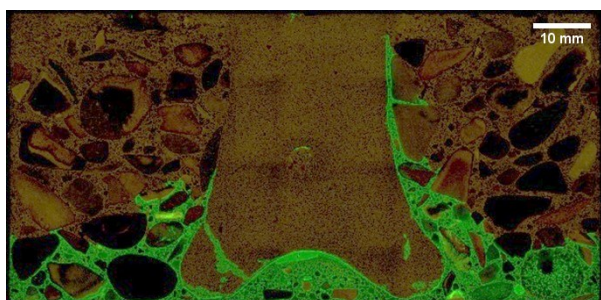
(f) C0.4-S3



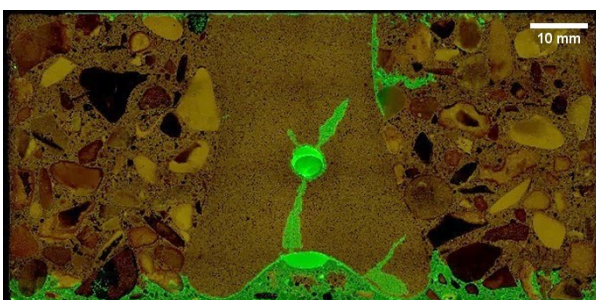
(g) C0.6-S4



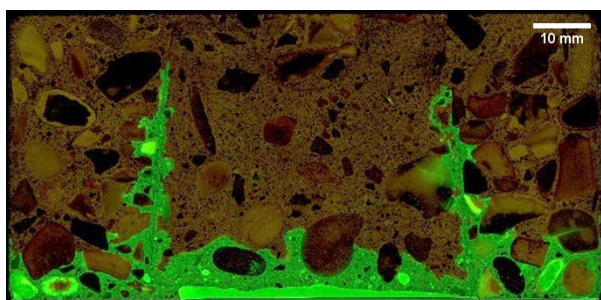
(h) C0.4-S4



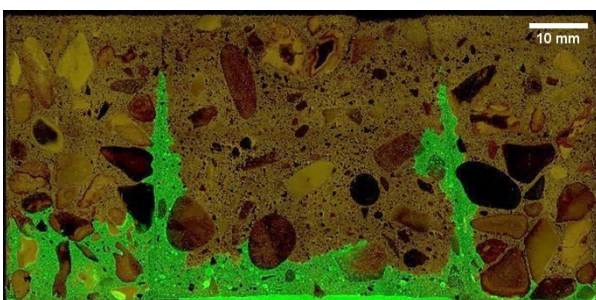
(i) C0.6-S5



(j) C0.4-S5



(k) C0.6-M1



(l) C0.4-M1

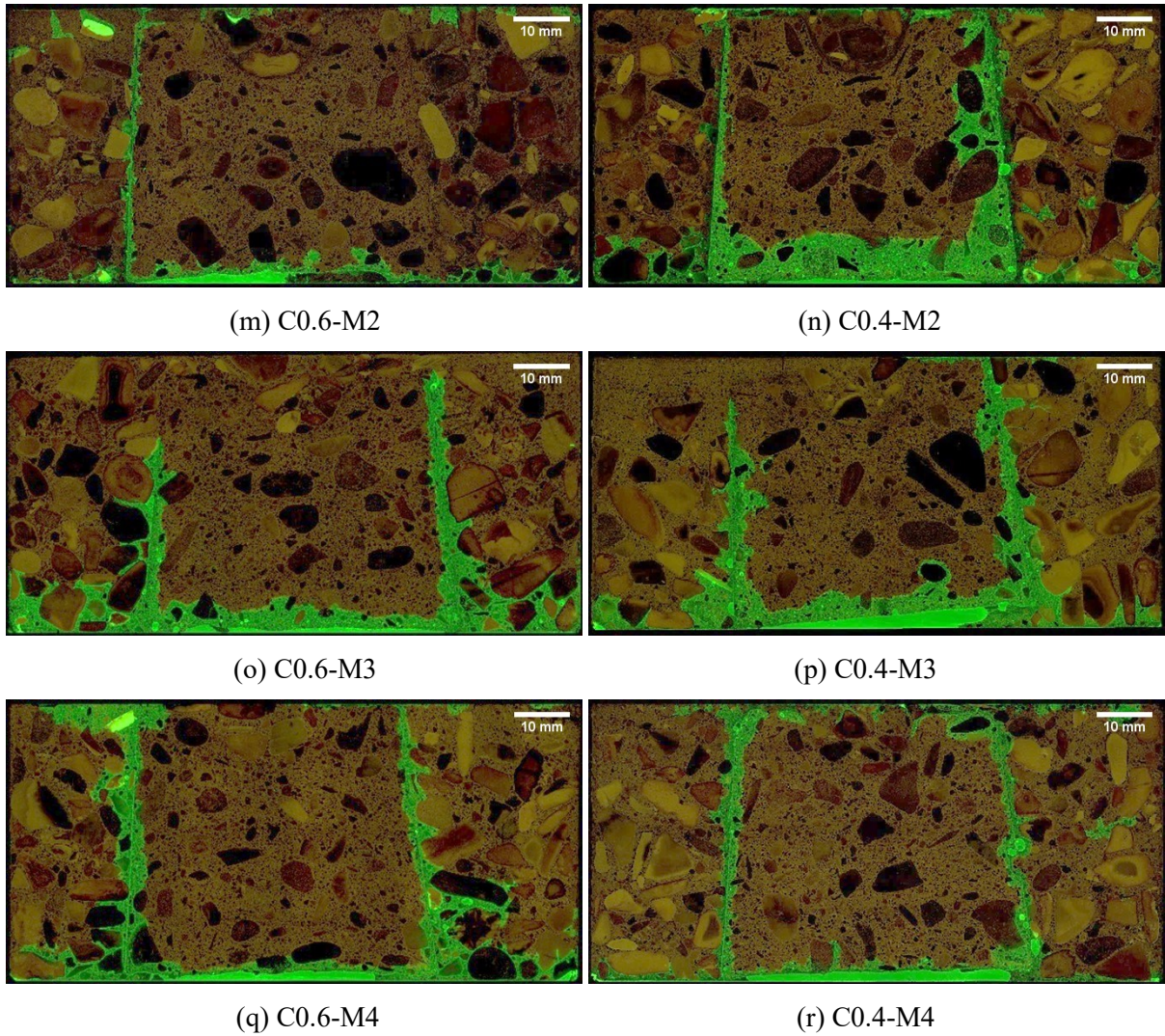


Figure 5.10 Stereo micrograph images showing fluorescent epoxy impregnation



Figure 5.11 Bottom surface of a typical M spacer showing an uneven base

Table 5.3 Maximum impregnation depths of spacer-concrete composites

Concrete	C0.6					C0.4				
Spacers	D _S (mm)	D _C (mm)	D _{IT} (mm)	T (mm)	D _{IT} /T (%)	D _S (mm)	D _C (mm)	D _{IT} (mm)	T (mm)	D _{IT} /T (%)
S1	11.2	12.0	27.6	45.3	60.8	7.6	5.6	36.0	51.3	70.2
S2	6.8	13.1	20.6	49.5	41.7	2.6	11.9	5.3	50.7	10.4
S3	5.1	6.3	50.0	50.0	100.0	5.5	45.45	52.0	52.0	100.0
S4	1.6	8.9	49.9	49.9	100.0	2.5	3.8	24.5	50.2	48.8
S5	14.0	21.7	47.1	50.6	93.2	35.5	9.1	50.2	50.2	100.0
M1	11.3	11.6	38.9	46.4	83.9	10.2	15.8	37.7	47.1	79.9
M2	5.7	4.1	46.1	46.1	100.0	8.7	9.3	46.9	46.9	100.0
M3	6.7	9.6	46.1	48.9	94.3	11.9	10.6	47.0	47.0	100.0
M4	4.3	16.4	47.4	47.4	100.0	7.4	3.9	49.6	49.6	100.0

Note: D_S, D_C and D_{IT} refers to the maximum impregnation depth through spacer, concrete and spacer-concrete interface respectively; T refers to the thickness of samples.

5.4 Conclusions

Effects of various cementitious spacers commonly used in the industry on the mass transport properties of the concrete cover were investigated in this chapter. Nine types of spacers were embedded in concrete at two w/c ratios, and their effects on oxygen diffusivity, oxygen permeability, water sorptivity and epoxy impregnation were investigated. The incorporation of these spacers was found to increase all mass transport properties, regardless of the w/c ratio of the concrete and the type of spacer used. Permeability was found to be most negatively affected and showed the highest variation in terms of the impact generated by different spacers. A more pronounced increase in mass transport properties was induced by the spacers when embedded in concrete with a low w/c ratio. In addition to the effects generated from the spacer-concrete interface, mass transport properties could be affected by the property of spacers. Sorptivity of spacer-concrete composites increased with the increase of the spacer sorptivity at low w/c ratio. Permeability of the composite samples was observed to have stronger correlation with spacer porosity than diffusivity and sorptivity. Epoxy impregnation was more substantial at the spacer-concrete interface compared to that occurring within the spacers or the bulk concrete. The impregnation depth varied depending on the spacer type, indicating variable bonding between spacer and concrete at different positions. All samples showed deep epoxy impregnation

through the spacer-concrete interface. Additionally, tie holes of S spacers and the bottom surface shape of certain spacer types could lead to compaction issues that affect the quality of the concrete cover.

Chapter 6 Enhancing the spacer-concrete interface by fibre-reinforcement

This chapter presents an investigation on developing cementitious spacers with fibres exposed on the surface for improving the spacer-concrete bonding and interfacial properties. Three types of fibres including steel fibre (SF), glass fibre (GF) and polypropylene fibre (PPF) were investigated. Effects of fibre length and dosage on spacer-concrete bonding were evaluated through measurement of the spacer-concrete bond strength, load-displacement characteristics, microstructure and mass transport properties.

6.1 Introduction

Cracking is a crucial factor affecting the long-term durability of concrete as it provides huge pathways for aggressive species to penetrate concrete structures. Substantial microcracking was observed in commercially available cementitious spacers investigated in Chapter 4 and at the spacer-concrete interface as demonstrated in Chapter 5 and some previous research (Alzyoud et al., 2016; Muslim et al., 2021b). The microcracking could be attributed to factors such as drying and autogenous shrinkage of spacers/concrete, damages occurring during the manufacture, storage and transport of spacers, and thermal incompatibility between spacers and concrete, etc.

Since 1960s, fibre reinforced concrete has been developed for reducing shrinkage-induced cracking, restraining growth of cracks, improving mechanical performance and durability properties (Daniel & Shah, 1994). Fibres can be categorised as either metallic, polymeric or natural in terms of their raw materials (Makul, 2021). Metallic fibres are made of carbon steel or stainless steel, and sometimes with coatings such as zinc for improving corrosion resistance or brass for improving bonding properties. These are widely used for improving the tensile and shear strength, ductility, fracture toughness and energy absorption capacity (Lee et al., 2021; Kim et al., 2019; Son et al., 2020; Vairagade & Kene, 2013).

Polymer fibres are commercially available in variety of compositions, e.g., polyolefin, polyester, nylon, acrylic and aramids, etc (Afroughsabet & Ozbakkaloglu, 2015; Xu et al., 2021). These are used to improve early-age properties of concrete including reducing plastic shrinkage, settlement cracks and bleeding, improving abrasion and impact resistance, and freeze-thaw resistance, and improving fire resistance of concrete (Lee et al., 2021; Kim et al.,

2019). Natural fibres include organic fibres such as silk, cotton, bamboo, oil palm and inorganic fibres such as asbestos and basalt. Natural fibre reinforced concrete is deemed to be more eco-friendly and ecologically beneficial, but require more care during production and placement. In addition, natural fibres could degrade and cause long-term performance issues (Shadheer et al., 2021).

Performance of fibre-reinforced concrete is dependent on the properties of the fibres, matrix and their bonding. The properties of the material, geometry, volume/mass fractions, orientation and distribution of fibres are generally considered as important factors from the perspective of fibres (Yoo et al., 2021; Abdallah et al., 2018; Zhao et al., 2021; Stucke & Majumdar, 1976; Butler et al., 2010). Material properties of fibres that have been widely investigated include tensile strength, elastic modulus, ductility, durability, Poisson's ratio and coefficient of thermal expansion (Rahmani et al., 2011; Afroughsabet & Ozbakkaloglu, 2015; Xu et al., 2021). Fibres with high elastic modulus are found to be more efficient for improving the tensile strength of concrete while fibres with low elastic modulus are preferable for improving the toughness of concrete (Banthia & Nandakumar, 2003; Pakravan et al., 2016).

Durability of fibres refers not only to their corrosion resistance but also to their compatibility with the high alkaline environment in concrete. Glass fibres and polyester fibres are likely to decompose in an alkaline environment and therefore various additives and surface treatments have been investigated to improve their stability in concrete (Rostami et al., 2020; Silva et al., 2005; Gao et al., 2003; Mirza & Soroushian, 2002). Poisson's ratio and coefficient of thermal expansion have significant effects on the bonding between fibres and the cement matrix (Bian et al., 2021; Abbood et al., 2021). Debonding is more likely to be induced by lateral contraction of fibre when their Poisson ratios are remarkably larger than that of the matrix. Increasing the mechanical anchorage by twisting fibres or adding surface roughness was found to be efficient in overcoming the high tendency of debonding (Deng et al., 2022).

Geometrical properties of fibres commonly taken into consideration include shape, length, aspect ratio (length/diameter ratio) or length/surface area ratio (Zhou et al., 2021; Moigne et al., 2011; Lee et al., 2021). Modifying the shape of fibre alongside their length generally aims at enhancing the bonding between fibre and matrix, and therefore increasing the tensile strength and restrain crack propagation of fibre reinforced concrete. This can be achieved by roughening the surface or inducing mechanical deformations and is highly used on metallic fibres (Antonova et al., 2021; Ding et al., 2020). Typical shapes alongside the length of fibres are

shown in Figure 6.1. Based on size parameters, fibres used in concrete can be categorised as macro-fibres and micro-fibres. According to BS EN 14845-2:2006 (2006), fibres with the diameter greater than 0.3 mm are classified as macro-fibres. Macro-fibres are more commonly used for improving strength and controlling cracks especially loading-induced cracking. Micro-fibres are preferable for reducing plastic shrinkage, increasing fire resistance and preventing concrete spalling (Reddy et al., 2021; Grdic et al., 2012). Increasing the length of fibres improves the tensile strength, shear strength and crack control. In some cases, long fibres have been used as a replacement for steel reinforcement (Mirza & Soroushian, 2002). However, over-long fibres could add difficulties to the mixing process and decrease workability of concrete (Figueiredo & Ceccato, 2015). Aspect ratio is another widely investigated parameter for quantifying the geometrical properties of fibres with circular cross sections. For fibres with non-circular cross sections, either the equivalent diameter or the length/surface area ratio is used in calculating aspect ratio (Suon et al., 2019). Compared to fibre length, the aspect ratio includes the effects of fibre cross section, shape and size. At constant fibre volume fraction and length, larger aspect ratios generally indicate higher number of fibres in the concrete mix.

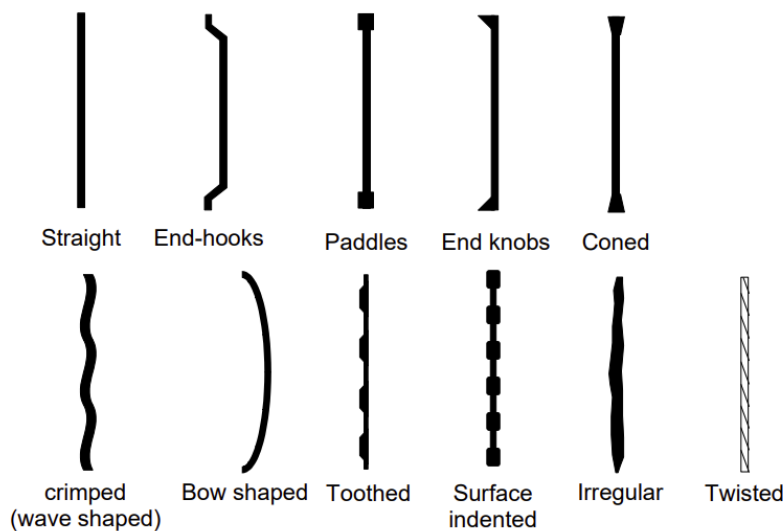


Figure 6.1 Typical shapes of fibres used in concrete (Tameemi, 2015)

The amount of fibres used in a concrete mix is commonly expressed as percentage of volume or mass to the total value of the composite. The optimal volume or mass fraction of fibres to be used in concrete depends on the material and geometrical properties, the intended application and the expected performance of the fibre-reinforced concrete. The use of excessive

amount of fibres is not only inefficient and costly, but also could lead to a decrease in workability properties (Figueiredo & Ceccato, 2015).

The orientation and distribution of fibres play important roles on the performance of fibre reinforced concrete (Zhao et al., 2021; Moigne et al., 2011). Without any special control, a random orientation of fibres can be achieved when sufficient compaction is applied and little bleeding is generated during concrete casting. Artificial control of the fibre direction can be achieved by using continuous filaments or plaits, or by pre-placing fibres on specially designed holders, or by 3D printing (Ferrara et al., 2011; Kang & Kim, 2011; Arunothayan et al., 2021). Magnetic force or an electromagnetic field have also been investigated to align the direction of metallic fibres (Ghailan & Al-Ghalib, 2020). Controlling the orientation of fibres could have a remarkable advantage on reducing cracking propagation especially with efficient design on the direction and number of fibres crossing the weak planes that are prone to cracking.

Addition of fibres improve both short-term and long-term performance of concrete. Furthermore, it has the potential to produce spacers that are more resistant to cracking. However, most commercially available spacers are plain cementitious materials and not fibre reinforced, as shown in Chapter 4. Addition of fibres would help improve crack resistance and achieve a better control of crack propagation in concrete. Spacers with exposed fibres on their surfaces would be expected to have better bond characteristics with concrete, and enhanced spacer-concrete interface. So far, no research has been carried out to produce and evaluate spacers with surface-exposed fibres. Therefore, in this chapter, three types of fibres of different lengths and volume fractions were investigated for producing fibre reinforced cementitious spacers. A new method for exposing fibres on the surface of spacers was proposed, tested and validated. The effect of these novel spacers on spacer-concrete bond strength, mass transport properties and microstructure were evaluated.

6.2 Experimental

6.2.1 Materials and mix proportions

The spacers developed in this chapter were made of fibre-reinforced mortar. Portland cement CEM I 52.5N and Thames Valley sand with maximum particle size of 5 mm were used. Mix

proportions were calculated according to the absolute volume method at water/cement (w/c) ratio of 0.3 and 0.4, and 50% total volume fraction of fine aggregate and fibre. The absorption and moisture content of the sand were tested frequently, and these were used to correct the mix proportions for aggregate absorption in order to achieve the target w/c ratios. MasterEase 3925 and MasterGlenium SKY 1901 were used as superplasticizers to improve workability of the mixtures with w/c ratio of 0.3 and 0.4 respectively.

Parameters related to fibres investigated in this chapter include their type, length and volume fraction. Steel fibre (SF), glass fibre (GF) and polypropylene fibre (PPF), as shown in Figure 6.2 were used. These were obtained from Rockbond Special Concrete Products (for SF) and Oscrete Construction Products (for GF and PPF). Basic properties of the fibres provided by the suppliers are listed in Table 6.1. To avoid possible degradation or corrosion, the fibres were kept sealed in plastic bags and stored in a cool and dry environment before casting. Selection of the fibre length was based on their commercial availability and the size of the cementitious spacer samples. On this basis, it was decided that SF with a length of 12 mm and 25 mm, GF of 12 mm long and PPF of 12 mm long were suitable for the investigation.

Trial mixes were carried out to determine the appropriate fibre volume, starting from 0.25%, 0.5%, 1% and 3% at water/cement (w/c) ratio of 0.4. The results show that 0.25 % vol. was too low, giving a very small number of fibres that would have limited potential in improving the performance of spacers and spacer-concrete interface. This was also the case with 25 mm SF, even when the dosage was increased to 0.5% vol. due to the high density of steel fibres. Therefore, these were not included in further investigations. However, increasing the fibre dosage caused a significant decrease in workability. Mortars containing 3% vol. GF or PPF were not sufficiently workable for casting spacers even at the maximum allowable superplasticizer dosage. Although the workability achieved with 3% vol. SF was adequate, this was not further investigated due to difficulties in exposing the fibres using the proposed method.

Final mix proportions of the fibre-reinforced mortar spacers are listed in Table 6.2. Control mortar spacers (without fibres) made prepared at the same w/c ratio and aggregate volume fraction for comparison. The naming convention of spacers follows the order of fibre type, length and volume fraction. For example, SF-12(0.5)-0.4 refers to the mortar spacer containing 12 mm SF at 0.5% volume fraction. The control mortar is simply referred to as M-0.4. Mix proportion of the concrete was also calculated according to the absolute volume method, at w/c ratio of 0.4, total aggregate content of 70% vol., and fine-to-total aggregate volume ratio of 0.4.

Thames Valley gravel with maximum particle size of 10 mm was used as coarse aggregate. Mix proportion of the concrete is shown in Table 6.3.



(a) SF (12 mm)



(b) SF (25 mm)



(c) GF (12 mm)



(d) PPF (12 mm)

Figure 6.2 Fibres used in this chapter

Table 6.1 Basic properties of the fibres

Fibre type	Diameter (mm)	Specific gravity (g/cm ³)	Tensile strength (MPa)
SF	0.4	7.8	850
GF	0.017	2.7	1700
PPF	0.024	0.9	340

Table 6.2 Mix proportions of fibre-reinforced cementitious spacers

Sample ID	Mix proportion				
	Cement (kg/m ³)	Sand (kg/m ³)	Fibre (kg/m ³)	Water (kg/m ³)	Superplasticizer (L/m ³)
M-0.3	803.1	1193.7	0.0	239.4	10.6
SF-12(0.5)-0.3	803.1	1181.7	39.0	239.1	10.9
SF-12(1)-0.3	803.1	1169.8	78.0	238.5	11.6
SF-25(1)-0.3	803.1	1169.8	78.0	238.5	11.6
GF-12(0.5)-0.3	803.1	1181.7	13.4	237.3	13.4
GF-12(1)-0.3	803.1	1169.8	26.8	235.9	15.2
PPF-12(0.5)-0.3	803.1	1181.7	4.6	236.5	14.4
PPF-12(1)-0.3	803.1	1169.8	9.1	235.5	15.7
M-0.4	692.0	1194.2	0.0	281.2	2.1
SF-12(0.5)-0.4	692.0	1181.7	39.0	282.0	1.4
SF-12(1)-0.4	692.0	1169.8	78.0	281.9	1.6
SF-25(1)-0.4	692.0	1169.8	78.0	281.9	1.6
GF-12(0.5)-0.4	692.0	1181.7	13.4	282.0	1.5
GF-12(1)-0.4	692.0	1182.7	26.8	268.3	2.6
PPF-12(0.5)-0.4	692.0	1181.7	4.6	279.4	5.3
PPF-12(1)-0.4	692.0	1169.8	9.1	275.7	10.4

Table 6.3 Mix proportion of concrete

Mix ID	w/c ratio	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (L/m ³)	Superplasticizer (L/m ³)
C0.4	0.4	418.14	715.05	1073.64	175.06	2.66

6.2.2 Sample preparation

Composite cylindrical samples consisting of half mortar spacer and the other half representing concrete were prepared. Cylindrical samples were used to facilitate strength and mass transport testing, and to enable direct comparison with results from Chapter 5 and from previous studies. The main steps in the preparation of spacer-concrete composite samples are summarised in Figure 6.3. First, the proposed splitting method described in Chapter 3.2 was used to prepare half-cylindrical mortar spacers with exposed fibres and unreacted cement particles while generating surface roughness at the same time. This was achieved by casting spacers with a prefabricated grooves and then splitting the spacer at these locations. As comparison, half-

cylindrical mortar spacers with flat cast surfaces were also prepared to simulate spacers that are currently used in the industry. Spacers produced with the proposed method are referred to as split spacers, while the ordinary spacers with flat surfaces are referred to as flat spacers in this chapter. The half-cylindrical spacers were cured in a fog room (100% RH, 21°C) for 7d, subsequently returned to the steel mould assembly and fresh concrete cast against the spacers (Figure 6.4). The spacer-concrete composite samples were then demoulded after 24h, cured (100% RH, 21°C) and conditioned (50°C for transport tests) for testing. The naming convention of the spacer-concrete composite samples follows the order of “type of spacer - material of spacer”. “Sp” and “F” represent split spacer and flat spacer respectively. It is worth noting that w/c ratio was shortlisted to 0.4 for producing spacers in composite samples, therefore w/c ratio was removed from the naming convention. For example, Sp-SF-12(0.5) refers to composite sample containing a split spacer with 0.5% vol. of 12 mm SF.

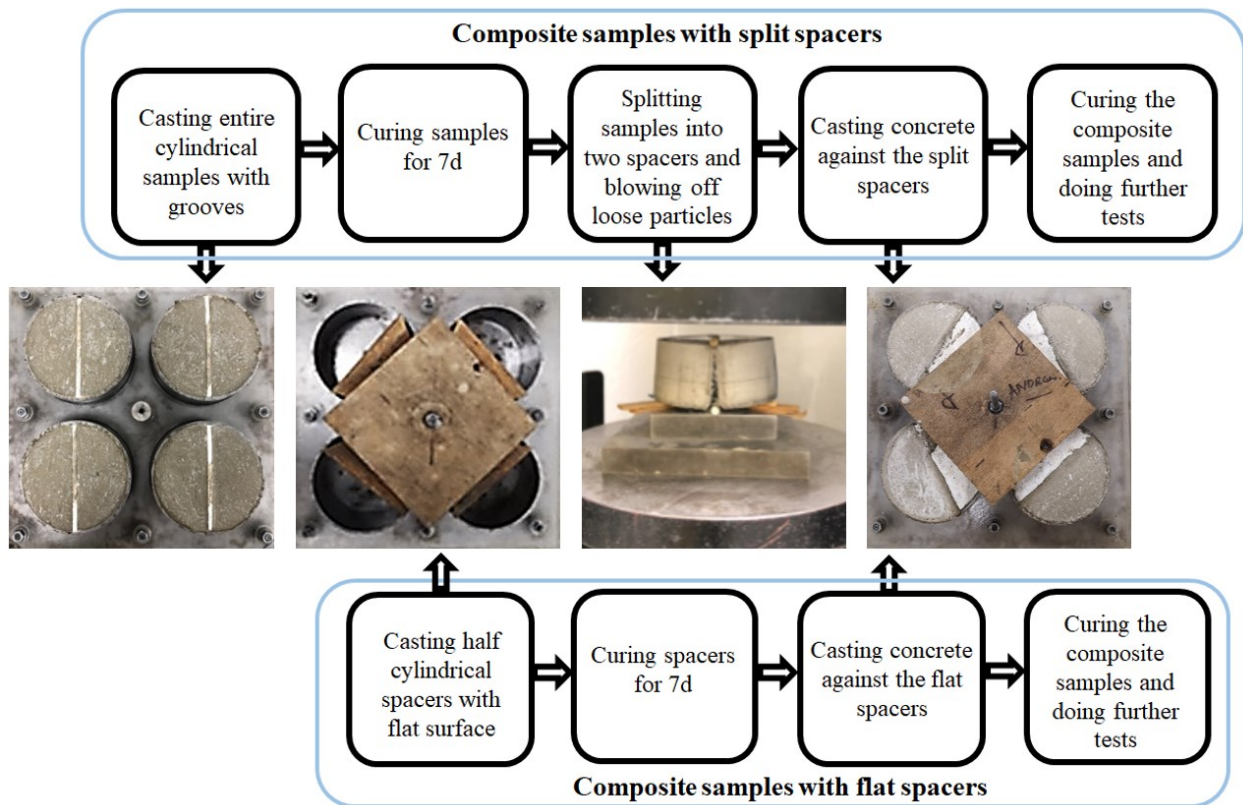


Figure 6.3 Preparation of spacer-concrete composite samples

6.2.3 Properties of fibre-reinforced cementitious spacers

The spacers produced in this chapter were tested for their compressive strength and mass transport properties. Compressive strength was measured to study the effect of fibres and to

ensure that the produced spacers comply with standard requirements (BS 7973-1:2001, 2001). Strength was measured on $50 \times 50 \times 50 \text{ mm}^3$ cubes in three replicates after curing in the fog room (100% RH, 21°C) to the ages of 3, 7, 14 and 28 days. Mass transport properties including oxygen diffusivity, oxygen permeability and water sorptivity were tested according to the procedures described in Chapter 3.4. This investigation mainly aimed at understanding the effects of the fibres, therefore mixes at w/c ratio of 0.4 were tested. Cylinders with diameter of 100 mm and thickness of 50 mm were prepared and cured for 7, 28 and 365 days, followed by conditioning at 50°C until constant weight. Mass transport properties were then measured on two to three replicates.

6.2.4 Bond strength and deformation

Bond strength between fibre-reinforced spacers and concrete was evaluated through tensile splitting test as described in Chapter 3.3.4. This investigation aimed at understanding the influence of fibres and the efficiency of the proposed spacer producing method, therefore mixes with w/c ratio of 0.4 were tested. Composite samples with split spacers and flat spacers were prepared and cured in a fog room at 21°C, 100% RH. For comparison, composite samples with spacers made of the control mortar (non fibre-reinforced) of same w/c ratio and aggregate volume fraction were also prepared and evaluated. Therefore, the variables include type of spacers (split or flat), type of fibres (SF, GF, PPF and none), lengths of fibres (12 and 25 mm), volume fraction of fibres (0.5% and 1%), and curing time of the composite samples (7, 14 and 28 days). Each strength result came from the average of four replicates.

Surface deformation of the composite samples with split fibre-reinforced spacers during bond strength test were evaluated with digital image correlation (DIC). Samples were cured for 28 days before tested. This investigation aimed at characterising the effects fibre-reinforced spacers on ductility and crack propagation at the spacer-concrete interface. Composites with control mortar spacers and flat spacers were not evaluated due to their brittle failure modes under bond strength test. Test setup and procedures for DIC were presented in Chapter 3.3.5. It is worth noting that the loading regime here was different from that of the bond strength testing. Loading was controlled by displacement at a rate of 0.1 mm/min in DIC tests for better capturing the transverse displacement and crack propagation at spacer-concrete interface, while

the bond strength tests were load-controlled at a rate of 0.03 MPa/s (BS EN 12390-6:2009, 2009).

6.2.5 Transport properties

Mass transport properties was conducted following the order of oxygen diffusivity, oxygen permeability and water sorptivity, as described in Chapter 3.4. Three replicates were prepared and tested for diffusivity and permeability, two replicates were tested for water sorptivity and the third remaining replicate was used for epoxy impregnation test. Composite samples with split spacers and flat spacers were prepared. The parameters investigated in these tests were the same as in bond strength tests, except that the curing time of the composite samples were 7, 28 and 365 days, in order to understand both the short-term and long-term curing on the mass transport properties. All samples were conditioned in the oven of 50°C until constant weight prior to the tests.

6.2.6 Fluorescent epoxy impregnation and image analysis

Composite samples with split spacers were benchmarked with composite samples with flat mortar spacers in the impregnation tests. One sample of each mix was cured for 28 days and then conditioned at 50°C before conducting the fluorescent impregnation test, following the steps described in Chapter 3.5. Samples were then sectioned from the middle and perpendicular to the spacer-concrete interface. The cut section was imaged with an Olympus SZX10 stereomicroscope under ultra-violet illumination to induce fluorescence, and the epoxy impregnation depth was measured using image analysis software ImageJ.

The impregnated samples were further cut into blocks with cross sections of 40 mm × 20 mm and thickness of 8 mm for microstructural characterisation using backscattered scanning electron (BSE) microscopy. The spacer-concrete interface was placed in the middle of the blocks alongside the 40 mm direction. Sample preparation for microscopy were conducted following the steps described in Chapter 3.6. Images at different magnifications (from 40× to 500×) were captured with BSE imaging and analysed.

6.3 Results and discussion

6.3.1 Properties of fibre-reinforced spacers

Compressive strength of the spacers at different ages is shown in Figure 6.4. As expected, compressive strength increased with the curing age, especially at early ages. Additionally, decreasing the w/c ratio from 0.4 to 0.3 could lead to an increase in compressive strength for all spacers and at all tested ages. However, addition of fibres had limited contributions to improving compressive strength. In fact, a decrease in compressive strength could be observed for the 0.3 w/c ratio regardless of the type, length, volume fraction of fibres, and curing age. At w/c ratio of 0.4, the difference in compressive strength between the fibre-reinforced spacers and control mortar spacers were relatively small.

At w/c ratio of 0.3, all mix proportions investigated exceeded the strength requirement of 50 MPa according to the standard (BS 7973-1:2001, 2001) after 3d curing. At w/c ratio of 0.4, it generally took 28d for most of the mixes to satisfy a compressive strength of at least 50 MPa. Therefore, the mix proportions at w/c ratio of 0.4 will be used for the rest of this chapter to investigate the efficiency of different fibre types and the proposed spacer production method. Another advantage of adopting a w/c ratio of 0.4 is that good workable mixes can be achieved without requiring a high dosage of superplasticizer. Additionally, a lower w/c ratio will increase cement content and this results in higher amount of unreactive cement particles, which increases the efficiency of the split spacers. Thus, if using fibre-reinforced spacers at w/c ratio of 0.4 is proven to be effective and beneficial, then moving to a lower w/c ratio would be expected to produce a better performance.

Test results of the mass transport properties of spacers are shown in Table 6.4. The 7d and 28d water sorptivity of the developed fibre-reinforced spacers lie within the range of results from the investigated commercial cementitious spacers (17.6 to 247.2 g/m²min^{0.5} according to Figure 4.17). At 365d, the fibre-reinforced spacers showed lower water sorptivity than all the investigated commercial cementitious spacers. Early-age mass transport properties of the developed fibre-reinforced spacers could be further improved by decreasing the w/c ratio, changing the curing regime or increasing the volume fraction of dense coarse aggregate particles.

The average values of fibre-reinforced spacers were normalised to the respective values of the control mortar spacers at the same curing age for comparison, as shown in Figure 6.5. The normalised values are all smaller than 1, which shows that addition of fibres decreased mass transport properties regardless of the fibre type, length, volume fraction and curing time. The greatest reduction was observed for permeability, followed by diffusivity and sorptivity after long-term curing (365d). However, the effect of fibre type and volume fraction on the magnitude of transport reduction was inconsistent. For spacers with SF and PPF, increasing the fibre volume fraction from 0.5% to 1% had limited beneficial effects on mass transport. For spacers with GF, a remarkable decrease in mass transport was generally observed with increase in GF volume fraction, especially for permeability. Increasing the length of SF from 12 to 25 mm caused a consistent reduction in all transport properties.

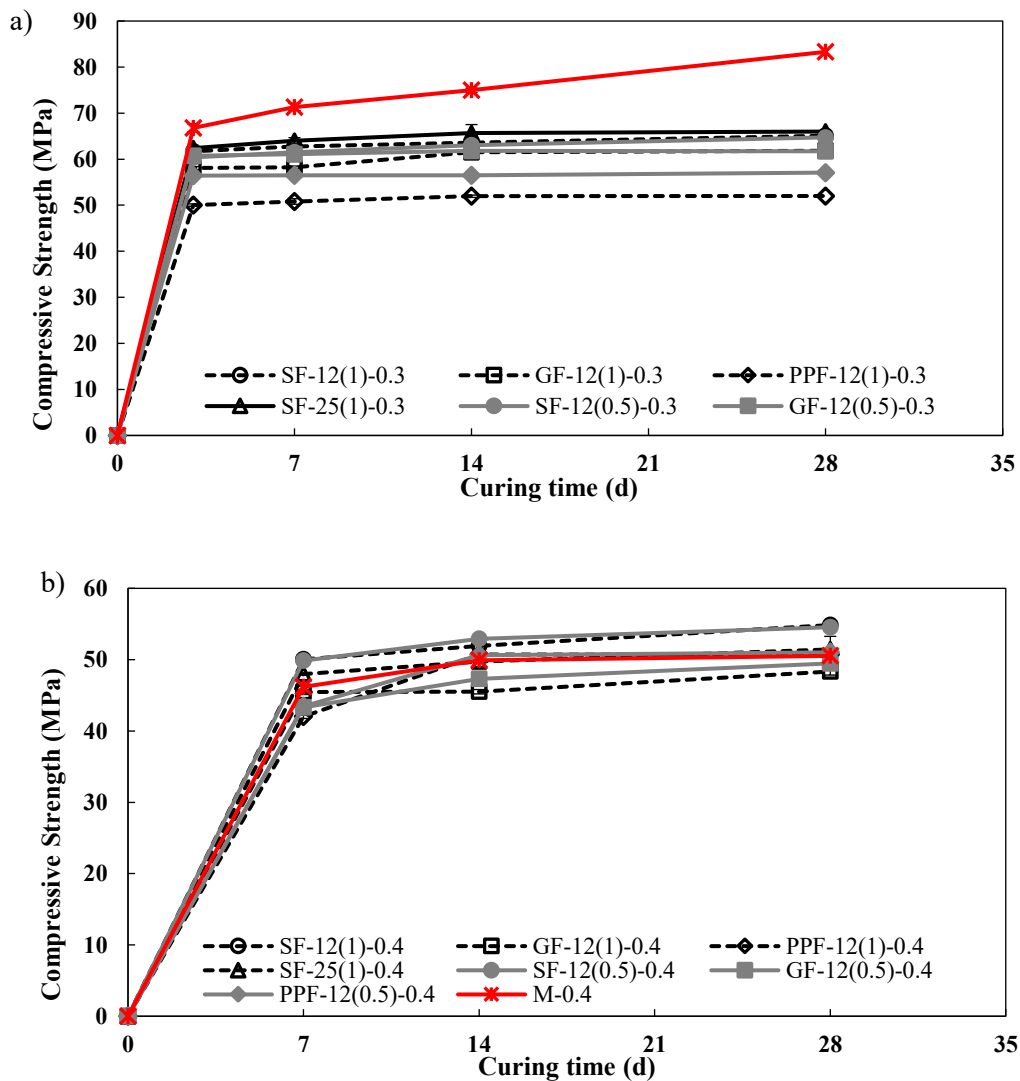


Figure 6.4 Compressive strength of fibre-reinforced spacers: a) w/c=0.3; b) w/c=0.4

Table 6.4 Mass transport properties of fibre-reinforced spacers

Properties	Diffusivity ($\times 10^{-8} \text{m}^2/\text{s}$)			Permeability ($\times 10^{-18} \text{m}^2$)			Sorptivity ($\text{g}/\text{m}^2 \text{min}^{0.5}$)		
Curing time (d) Spacers	7	28	365	7	28	365	7	28	365
M-0.4	18.07 (0.04)	14.37 (0.13)	3.28 (0.04)	60.54 (0.51)	42.43 (0.99)	5.60 (0.07)	185.17 (4.98)	145.74 (6.21)	20.51 (0.08)
SF- 12(0.5)-0.4	14.97 (0.06)	12.70 (0.10)	3.01 (0.04)	52.27 (0.35)	40.77 (0.26)	4.87 (0.04)	137.94 (5.40)	120.27 (3.29)	17.02 (0.99)
SF- 12(1)-0.4	15.05 (0.27)	12.35 (0.11)	2.99 (0.10)	46.83 (0.35)	37.17 (0.45)	4.14 (0.02)	169.08 (4.35)	139.09 (0.40)	18.17 (1.29)
SF- 25(1)-0.4	13.55 (0.13)	12.14 (0.14)	1.84 (0.003)	31.27 (0.31)	28.08 (0.26)	3.11 (0.04)	138.29 (8.11)	113.66 (4.72)	18.91 (0.84)
GF- 12(0.5)-0.4	15.93 (0.23)	13.75 (0.14)	2.45 (0.02)	42.11 (0.40)	39.21 (0.25)	5.42 (0.09)	145.69 (1.57)	130.57 (1.57)	18.50 (1.46)
GF- 12(1)-0.4	12.79 (0.03)	12.38 (0.12)	1.61 (0.06)	27.27 (0.20)	22.98 (0.17)	1.49 (0.06)	137.53 (6.90)	96.43 (2.36)	15.13 (1.06)
PPF- 12(0.5)-0.4	12.56 (0.10)	11.66 (0.03)	1.28 (0.02)	15.77 (2.32)	13.57 (0.43)	0.95 (0.00)	105.62 (3.79)	87.31 (1.45)	16.41 (0.14)
PPF- 12(1)-0.4	14.65 (0.19)	12.41 (0.08)	2.34 (0.06)	42.67 (0.33)	40.84 (0.37)	1.40 (0.04)	132.3 (0.06)	123.98 (0.08)	17.71 (0.30)

Note: Standard deviation is indicated in brackets.

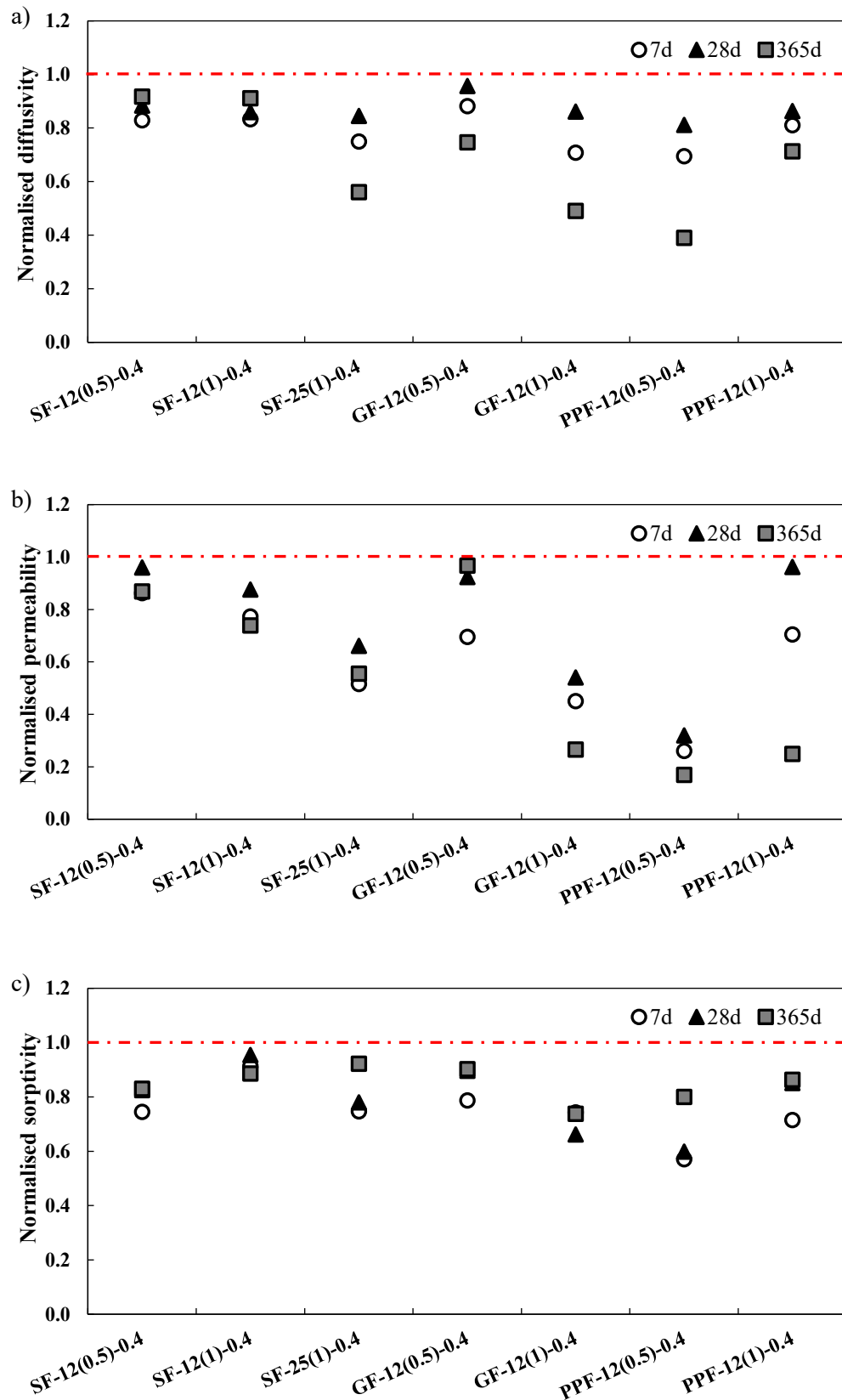


Figure 6.5 Mass transport properties of fibre-reinforced spacers: a) diffusivity; b) permeability; c) sorptivity. The data are normalised to the respective values of control mortar spacers at same age

6.3.2 Influence of fibre-reinforced spacers on bonding behaviour with concrete

6.3.2.1 Bond strength

Results of the spacer-concrete composite bond strength are listed in Table 6.5. To better appreciate the effects induced by fibre-reinforcement and the proposed spacer manufacturing method, the bond strength results are normalised to that of the control composite sample (F-M, flat spacers, non-fibre reinforced) at the respective curing time. This is comparable with commercial spacers that generally have cast smooth surfaces to bond with concrete. The normalised values are shown in Figure 6.6. The normalised bond strength data of composites with flat spacers ranged between 0.98 and 1.05, showing marginal change with fibre type, volume fraction, length or curing time. A typical de-bonding failure mode at the spacer-concrete interface, as shown in Figure 6.7a, was observed for all tested samples with flat spacer. The results indicate that addition of fibres into spacers without exposing them to the spacer-concrete interface produced limited contributions to improving bond strength.

Table 6.5 Bond strength results of fibre-reinforced spacer-concrete composite

Curing time (d)	7		14		28	
Spacers contained	Flat	Split	Flat	Split	Flat	Split
M	2.09 (0.11)	3.11 (0.18)	2.14 (0.17)	3.46 (0.07)	2.48 (0.10)	3.88 (0.14)
SF-12(0.5)	2.13 (0.04)	3.41 (0.10)	2.14 (0.12)	3.98 (0.35)	2.47 (0.09)	4.11 (0.08)
SF-12(1)	2.20 (0.09)	3.49 (0.03)	2.24 (0.09)	3.77 (0.23)	2.48 (0.17)	4.06 (0.14)
SF-25(1)	2.07 (0.11)	3.47 (0.04)	2.16 (0.10)	3.72 (0.22)	2.42 (0.14)	4.20 (0.09)
GF-12(0.5)	2.08 (0.14)	2.97 (0.08)	2.11 (0.09)	3.30 (0.06)	2.50 (0.20)	3.67 (0.14)
GF-12(1)	2.15 (0.03)	3.14 (0.03)	2.15 (0.15)	3.56 (0.12)	2.51 (0.15)	4.03 (0.07)
PPF-12(0.5)	2.14 (0.06)	2.96 (0.13)	2.18 (0.11)	3.43 (0.08)	2.53 (0.11)	3.69 (0.12)
PPF-12(1)	2.11 (0.12)	3.11 (0.14)	2.13 (0.19)	3.53 (0.18)	2.51 (0.15)	3.93 (0.15)

Note: Unit of the data is MPa; Standard deviation is indicated in brackets.

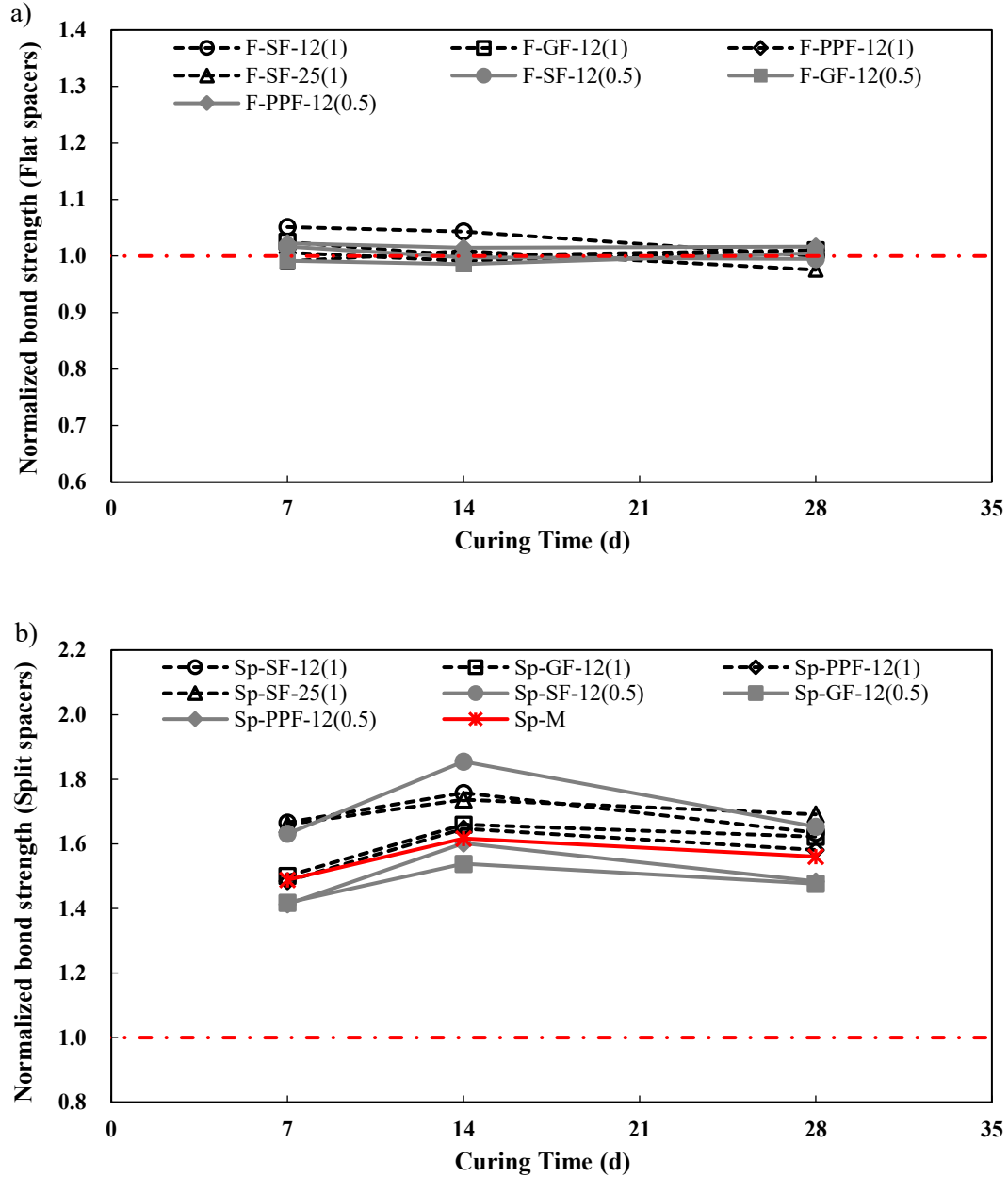


Figure 6.6 Bond strength of spacer-concrete composites: a) flat spacers; b) split spacers. The data is normalised to bond strength of the control composite sample (F-M) at respective age

In contrast, all composite samples with split spacers had normalised bond strength values much higher than 1, as shown in Figure 6.7b. This ranged from 1.41 to 1.85, which suggests substantial improvement in bond strength with split spacers. Observations made on the split spacer-concrete composites found multiple failure modes, such as fracturing of the spacer, fracturing of the concrete and fibre-matrix de-bonding, as shown in Figure 6.7b. Therefore, the increase in bond strength could be attributed to a number of factors, such the increased surface roughness, hydration of the freshly exposed cement particles and the interaction between fibre

and concrete. For composite samples containing spacers of the same composition, a mild increase in the normalised strength values was observed with curing age, which suggests that this is dependent on the gradual strength development of the control sample from 7d onwards.

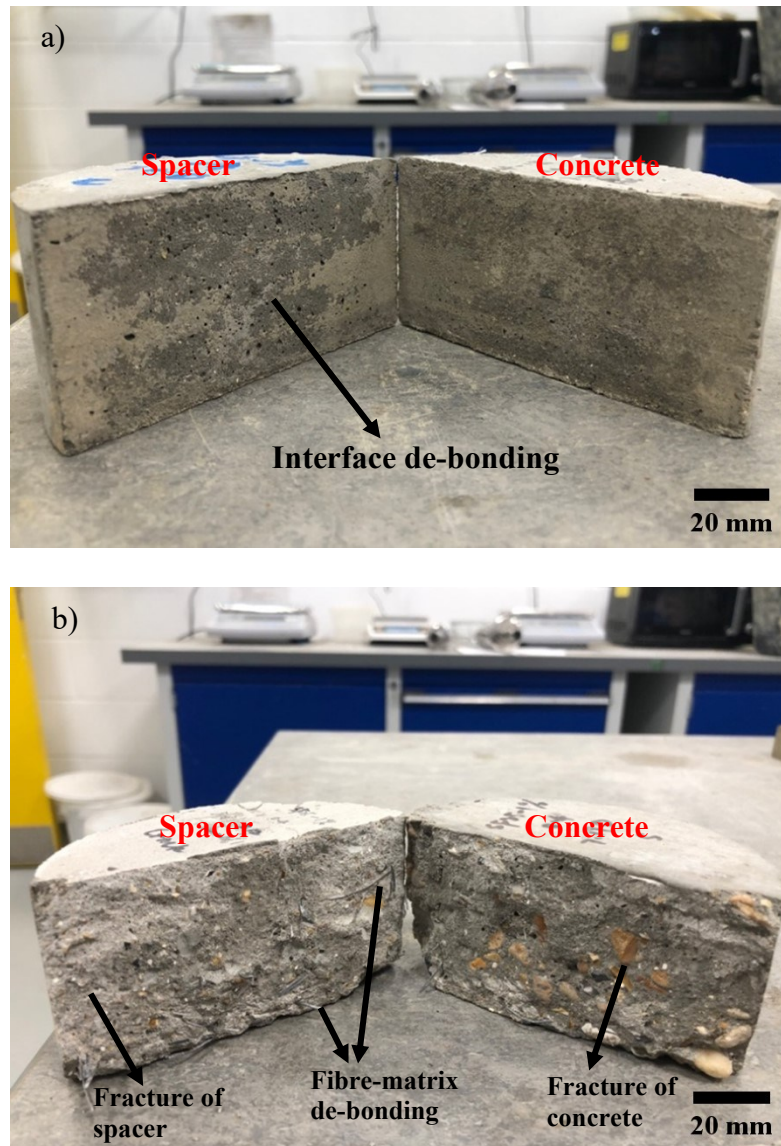


Figure 6.7 Typical failure modes for spacer-concrete composites containing: a) flat spacer; b) fibre -reinforced split spacer

At equal fibre volume fraction, spacers with exposed SF showed the highest bond strength with concrete, followed by GF and PPF. However, a limited improvement was observed when the length of SF was increased from 12 to 25 mm, and a similar trend was also observed when doubling the volume fraction of the 12 mm SF. In comparison, increasing the volume fraction

of GF and PPF were more beneficial than SF for improving bond strength. It is suspected that these trends are probably dependent on the number and length of the fibres exposed at the spacer-concrete interface. Therefore, the characteristics of exposed fibres (number, length) were evaluated on the split spacers and presented in Figure 6.8. Unfortunately, PPF had the tendency to clump which made it very difficult to measure individual fibres and thus they were not included here. The measurement was conducted after removing the loose fibres from the surface of the split spacers, and results shown in Figure 6.9 were based on the average of 54 replicate split spacers.

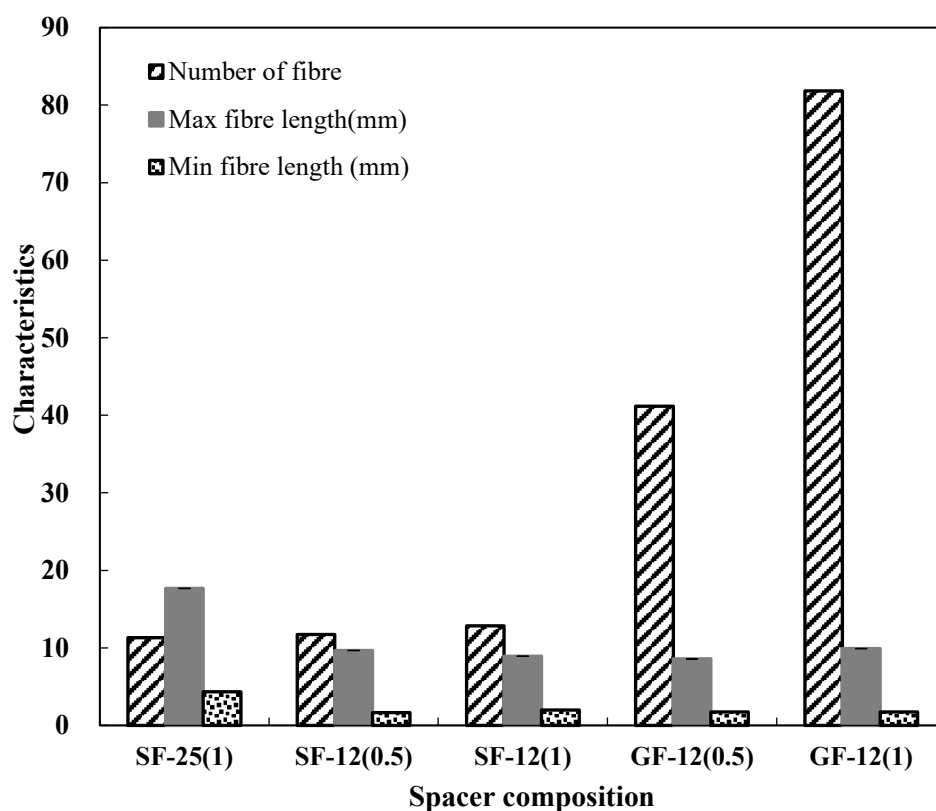


Figure 6.8 Characteristics of fibres exposed on the surface of split spacers

For spacers reinforced with SF, the number of exposed fibres were in a narrow range between 9 and 14, regardless of volume fraction and length. This was unexpected because theoretically, the number of fibres in the spacers should be dependent on their volume fraction and length (for constant fibre diameter). However, it was found that the number of fibres exposed on the surface of the split spacers remained relatively consistent. Therefore, it is suspected that the fibre volume fractions used in the mix design were too low to expose enough number of SF

due to the high density of steel, which made it difficult to detect any differences between mixes. However, trials have shown that increasing the SF volume fraction caused problems with splitting the spacers without generating secondary cracks. Thus, using SF with smaller diameters could be a potential improvement to be considered in future investigations. In contrast, for spacers reinforced with GF, the number of exposed fibres doubled with the doubling of their volume fraction, at around 40 and 80 when using 0.5% and 1% vol. respectively.

As expected, the maximum and minimum lengths of exposed fibres were dependent on the length of the fibres involved. The maximum and minimum values for spacers with 25 mm long fibres were around 18 and 4 mm respectively, decreasing to around 10 and 2 mm for spacers with 12 mm long fibres regardless of the fibre type. Additionally, the standard deviations of all measured characteristics were relatively small, which suggest a good repeatability of the spacer producing method. It is also worth noting that other factors such as the orientation and alignment of the exposed fibres could influence the bonding behaviour between spacers and concrete. In this study, the exposed fibres were randomly distributed and orientated. Therefore, innovative methods for controlling the direction of fibres could be further investigated in order to achieve an optimal effect.

Figure 6.6b shows that all split spacers containing SF at 0.5% and 1% volume fraction improved bond strength compared to the mortar split spacers (non-fibre reinforced). However, the use of GF and PPF is only beneficial at the higher volume fraction of 1%. This could be related to the potential limitations of the spacer producing method. On the one hand, splitting spacers containing with fibres could generate additional microcracks or release loose cement particles around the split surface. On the other hand, exposing one fibre on one side means generating a void on the other side of the spacer. These voids could be beneficial for bonding if they are subsequently filled with cement pastes or hydration products from the cast concrete, but otherwise could be detrimental. Many factors would influence this such as the diameter, depth, number, and alignment of the voids, the flowability and compaction of the concrete etc.

Additionally, because bond strength was evaluated through tensile splitting, fibres that are parallel or aligned to the interface will offer little contributions. Benefits of inclined fibres are also likely to be attenuated in terms of the bond strength under tensile stress. Although the disadvantages mentioned here seem to be more serious when increasing the fibre volume

fraction, it is difficult to quantify these impacts, and it is harder to say whether they will counteract the benefits brought by increasing fibre volume.

6.3.2.2 Deformation

Through the bond strength tests, it was observed that samples with fibre-reinforced split spacers showed substantial ductile behaviour, with significant deformation occurring prior to ultimate failure. This is in contrast with the control composite samples (F-M) that failed in a sudden brittle manner. The ductile behaviour might be advantageous for controlling cracking around spacer-concrete interface and therefore the long-term durability of concrete. To study this in greater detail, the transverse deformation and crack propagation on the surface of samples with fibre-reinforced split spacers were followed via Digital Image Correlation (DIC). The bond strength and number of fibres exposed during DIC, and tensile splitting are compared in Table 6.6. The number of exposed fibres were found to be similar except for samples with SF-12(0.5) spacers. The bond strengths obtained from DIC were generally 90% of the respective values from direct tensile splitting tests. This is probably due to the slower loading rate used in DIC, which allowed cracks to propagate more and therefore reducing the ultimate stress of these samples.

Table 6.6 Results from DIC and comparison with results from direct tensile splitting

Samples	DIC				Direct tensile splitting test		
	G_f (kJ/m ³)	G_u ($\times 10^{-3}$ kJ/m ³)	$N_{f,dic}$	$f_{fS,dic}$ (MPa)	N_f	f_{fS} (MPa)	$f_{fS,dic}/f_{fS}$
Sp-SF-12(0.5)	274.31	1.71	9	3.25	13	4.11	0.79
Sp-SF-12(1)	66.95	2.58	14	3.79	14	4.06	0.93
Sp-SF-25(1)	1431.16	23.85	13	4.11	14	4.20	0.98
Sp-GF-12(0.5)	1237.74	6.65	42	3.28	41	3.67	0.89
Sp-GF-12(1)	5768.72	16.31	83	3.60	84	4.03	0.89
Sp-PPF-12(0.5)	3864.73	1.64	-	3.20	-	3.69	0.87
Sp-PPF-12(1)	5943.44	14.72	-	3.66	-	3.93	0.93

Notation: G_f and G_u represent the energy absorbed at failure and ultimate stress respectively; $N_{f,dic}$ and N_f represent average number of fibres exposed to the surface of spacers in DIC tests and direct tensile splitting test. $f_{fS,dic}$ and f_{fS} represent bond strength obtained through DIC test and direct tensile splitting test.

Analysis of the strain distribution and development were conducted through the DaVis software. A rectangular area of 4 mm × 2 mm was selected for analysing the transverse strain development of each sample. The area was selected across the main crack with minimal inclusion of the uncracked area to avoid dilution of transverse strain, as shown in Figure 6.9.

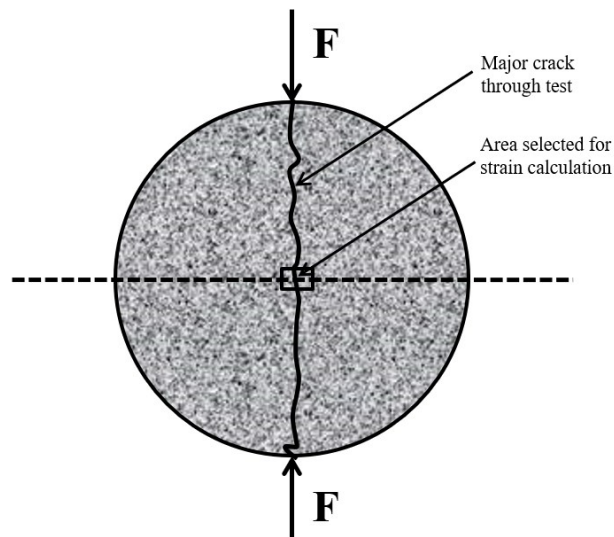


Figure 6.9 Area for analysing transverse strain through DIC

Figure 6.10 presents the stress against transverse strain relationship, where figure (a) shows the strain development through the entire test until the sample failed (split), and figure (b) shows the strain development up to reaching the ultimate stress. A clear strain softening stage could be seen for most samples, which indicates the improved ductility introduced by spacers with exposed fibres. This is attributed to the bridging effects induced by fibres across the spacer-concrete interface, as shown in Figure 6.11. The increased ductility would be beneficial for postponing the spalling of concrete cover under ultimate limit state, as well as bringing economic benefits for concrete rehabilitation.

The energy absorbed during DIC testing was analysed by calculating the area under the stress-strain curve. The results presented in Table 6.6, show that for the same fibre volume fraction, spacers with PPF were the most effective, followed by those with GF and SF. A significant increase in the absorbed energy could be seen with the increase in volume fraction of PPF and GF. Unexpectedly, SF had limited benefits in postponing ultimate failure compared to samples

with PPF or GF at same volume fraction. Samples with short SF (12 mm) showed a more brittle failure mode which occurred soon after reaching the ultimate stress. This is related to the smaller number of fibres across the spacer-concrete interface, which decreased the fibre bridging effects.

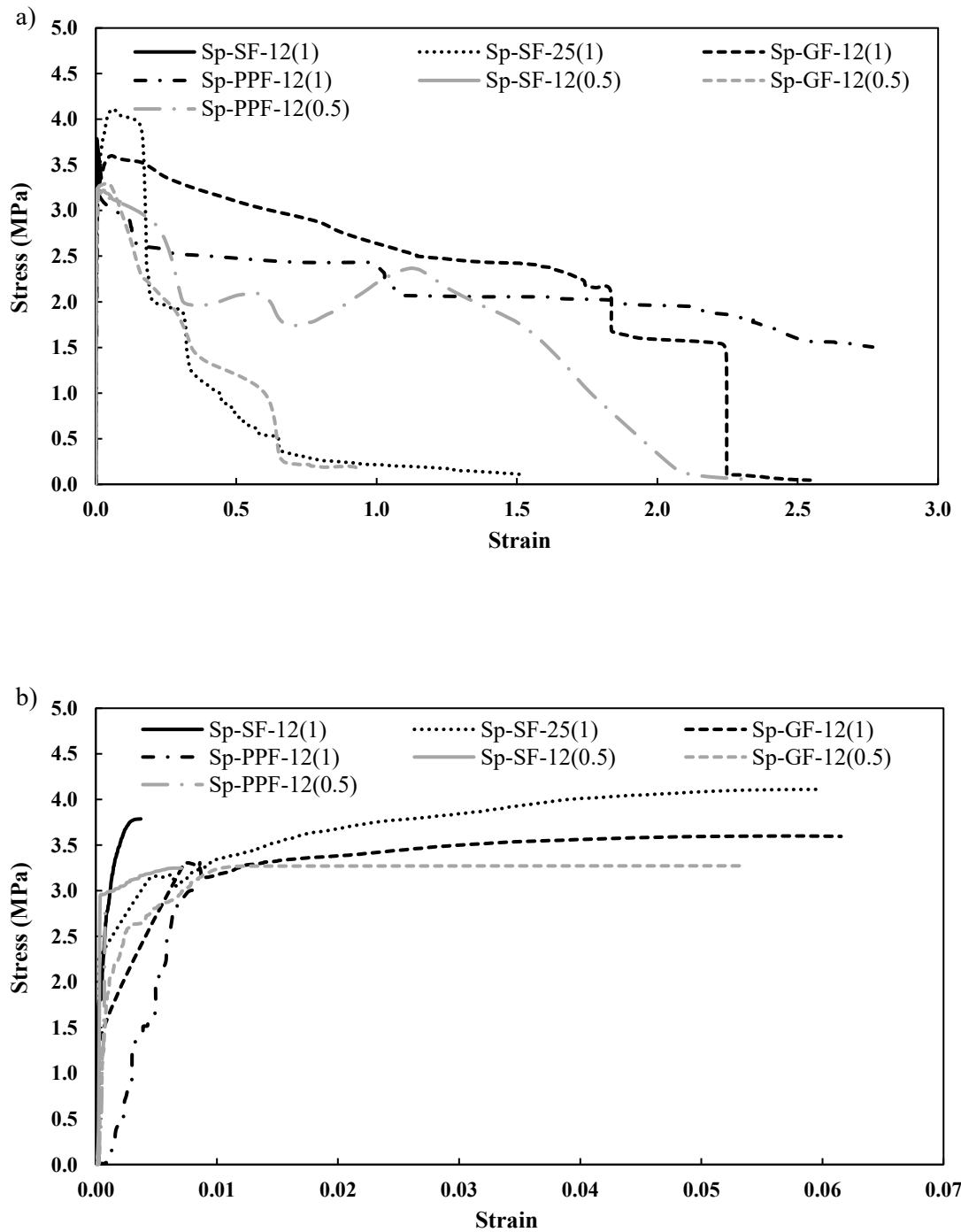


Figure 6.10 Stress to transverse strain relationship plotted up to: a) sample failure; b) ultimate stress

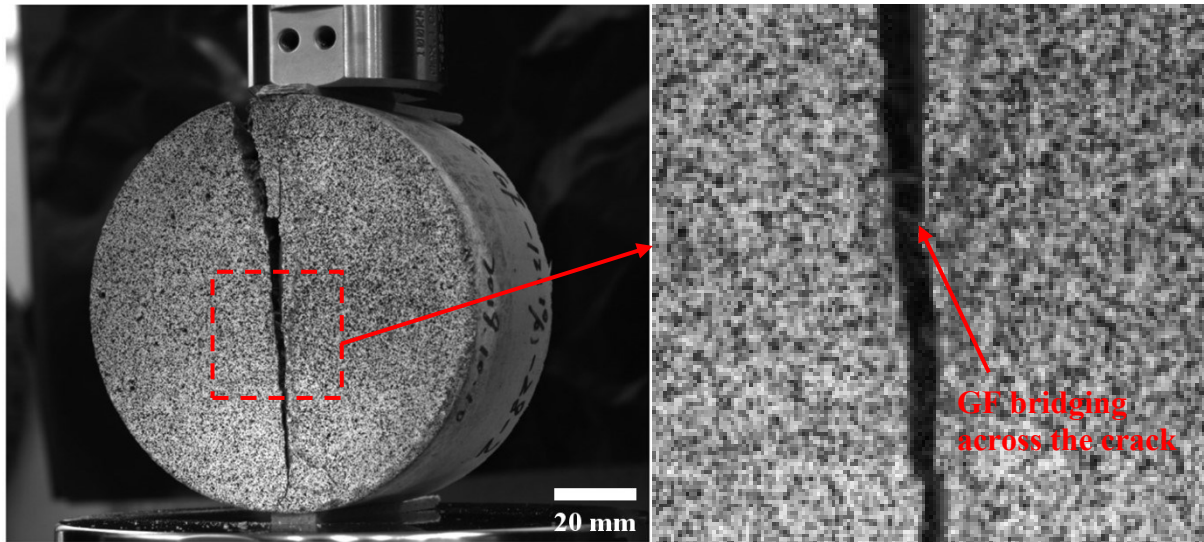
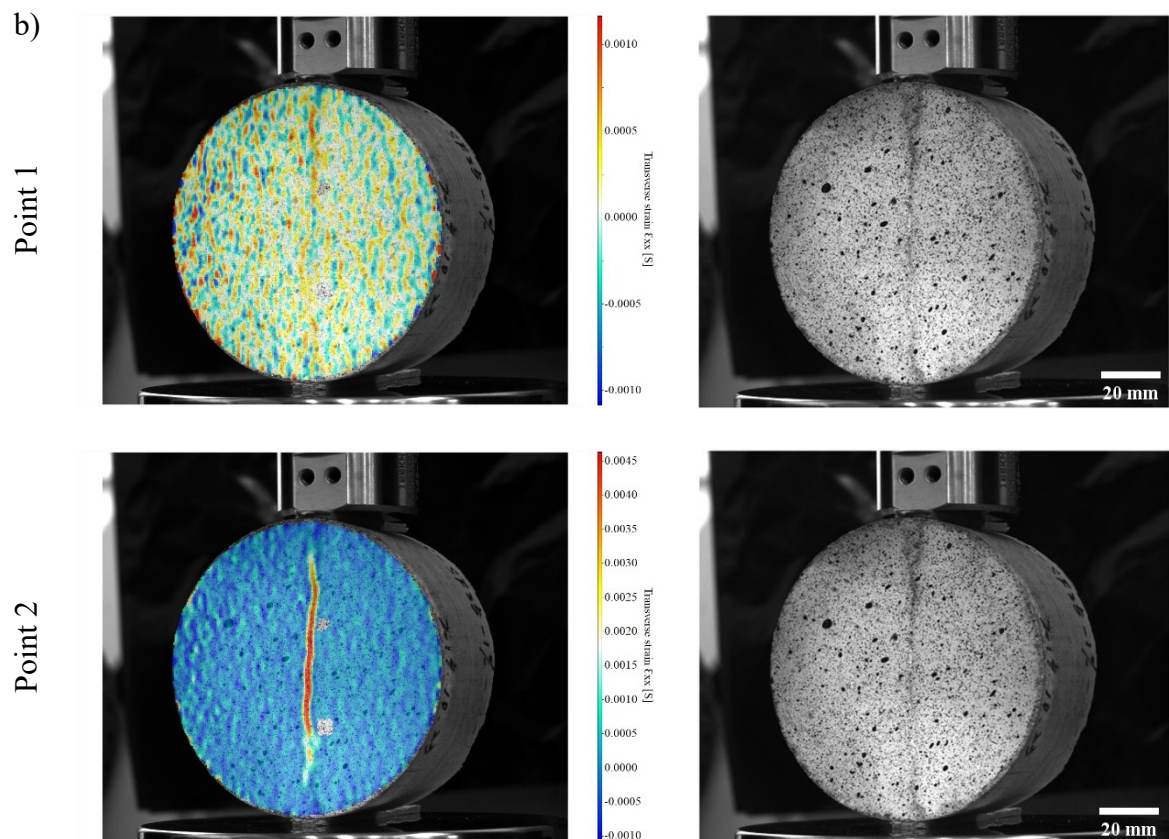
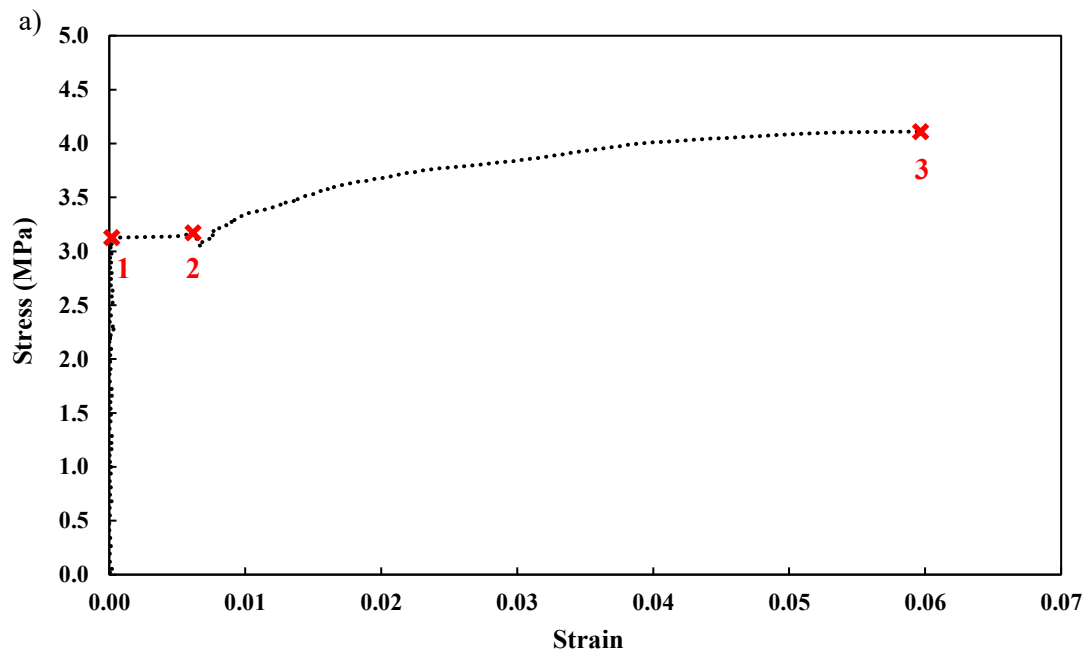


Figure 6.11 Fibre bridging across the spacer-concrete interface (Sp-GF-12(1))

The stress-strain data prior to reaching the ultimate stress were extracted and analysed, as these are more relevant to the performance of concrete structures during normal service conditions. Non-linear behaviour could be seen on all samples due to the heterogeneity and gradual propagation of cracks. The strain distribution and crack initiation and propagation phenomenon were analysed carefully especially at some critical points shown on the stress-strain curve. Here the sample with spacer SF-25(1) is interpreted in detail in Figure 6.12 as an example. The first obvious inflection is marked as point 1, from which a large increase in strain occurred up to point 2. Figure 6.12b shows that strain was distributed homogeneously across the surface at point 1 and that large local strains along the spacer-concrete interface were observed for the first time at point 2. It is suspected that this marks the propagation of microcracking although no obvious cracking could be visually detected on the surface of the sample at this stage. A small drop in stress occurred after point 2, which is likely induced by the microcrack propagation. Afterwards, strain increased nonlinearly with increase in stress until reaching ultimate failure (point 3). The area with large localised strain kept developing along the spacer-concrete interface until the first visible crack was detected on the surface of the sample, coinciding with point 3 on the stress-strain curve. Similar stress-strain curves and cracking phenomenon were observed on other samples with SF and GF.



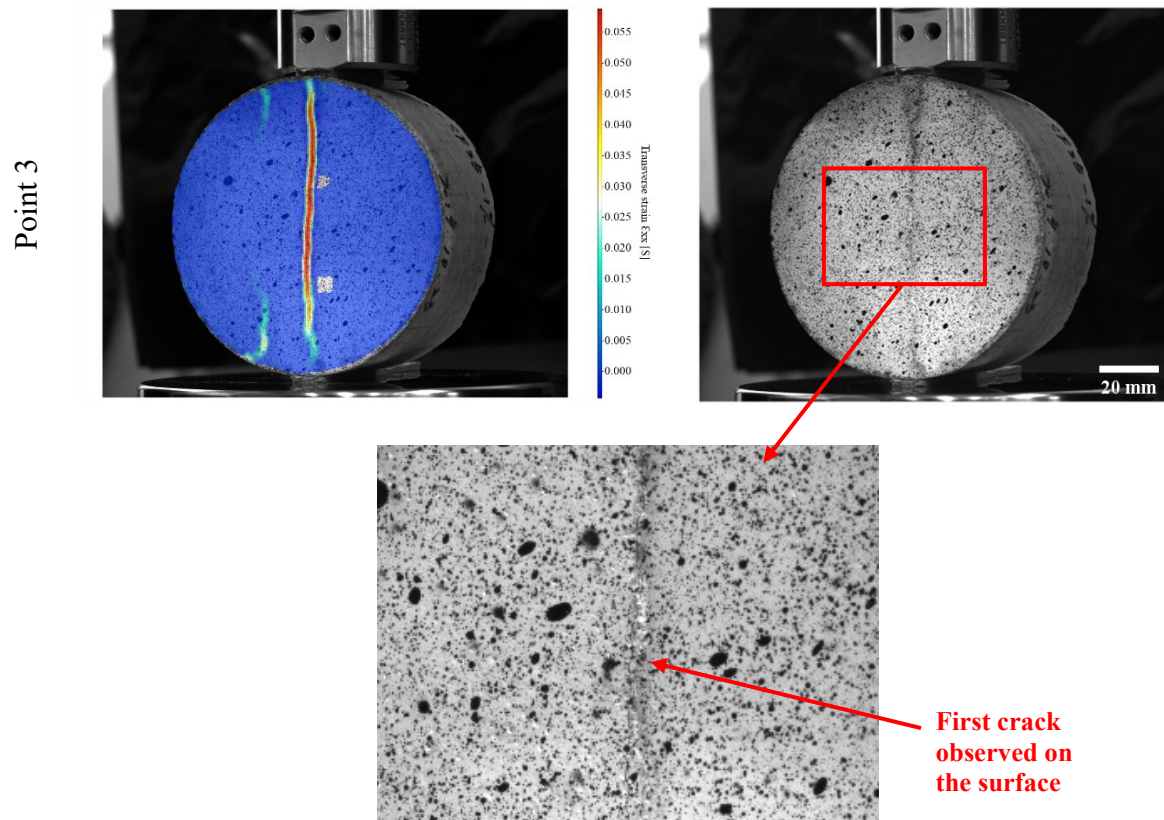
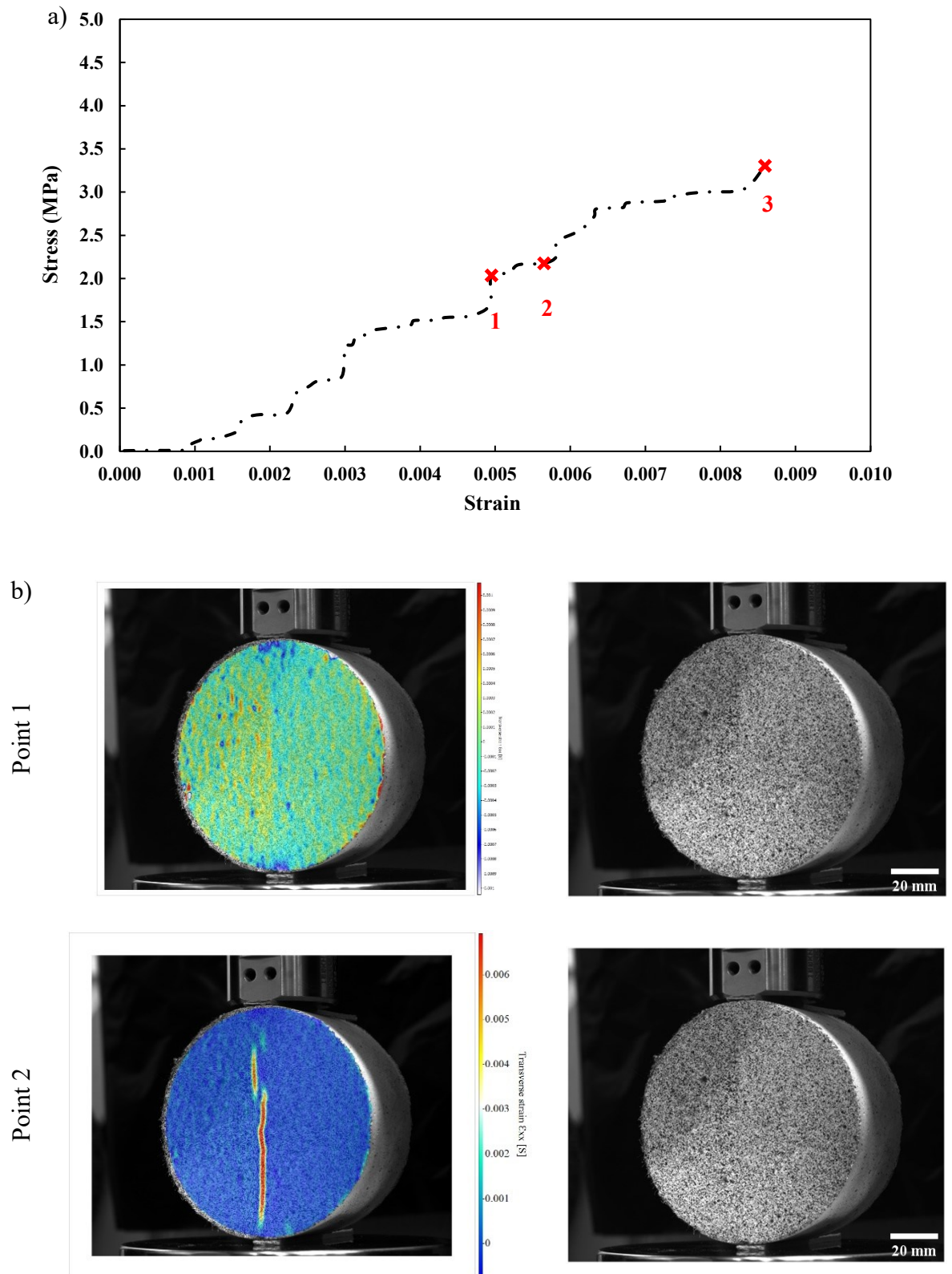


Figure 6.12 Stress-strain distribution and crack initiation of sample Sp-SF-25(1): a) stress-strain distribution; b) crack initiation

However, slight differences were observed on samples containing PPF, as shown in Figure 6.13. No obvious linear segments could be observed on the stress-strain curve. Strain development was relatively homogenous up to point 1 and the first appearance of localised strain at the spacer-concrete interface could be seen appearing at point 2. Yet it was difficult to detect any differences on the stress-strain curve prior to or after point 2. Ultimate stress was achieved at point 3, which also coincided with the first visual observation of cracking on the surface of the sample.

The area under the stress-strain curve before reaching ultimate stress (G_u) is listed in Table 6.6. This quantifies the ability of the sample to absorb energy up to the first visible crack on the surface, and indicates the ability to delay cracking at the spacer-concrete interface. The sample with SF-25(1) spacer was found to be most effective, followed by GF-12(1) and PPF-12(1). Short SF was again found to bring limited benefits. Increasing the fibre volume was found to be highly beneficial for increasing G_u , especially for samples with PPF. Additionally, for samples reinforced with SF-25 and GF-12, their strains at the generation of first visible crack

were much larger than other samples. This suggests a better crack control at the spacer-concrete interface, especially for delaying the development of shrinkage and/or thermal cracks.



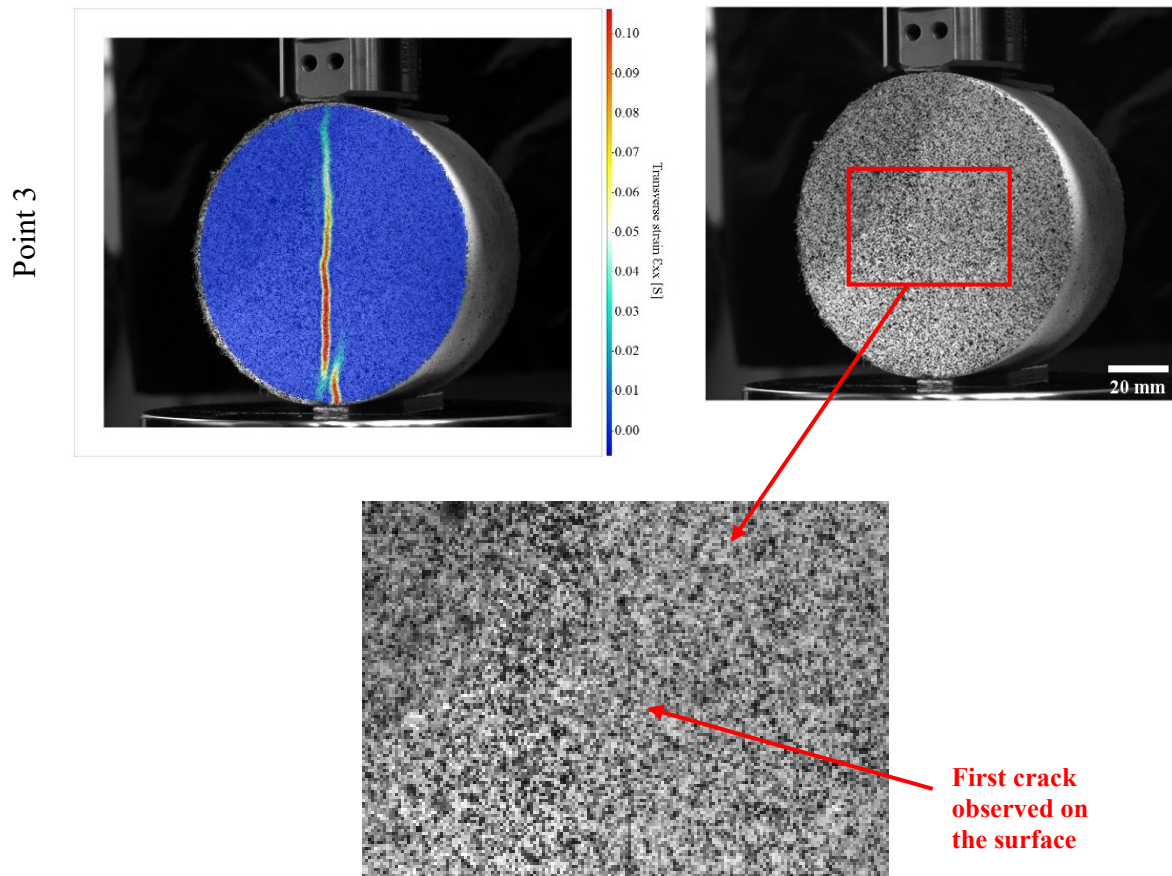


Figure 6.13 Strain distribution and crack initiation of sample Sp-PPF-12(1): a) stress-strain distribution; b) crack initiation

6.3.3 Influence of fibre-reinforced spacers on mass transport properties

Mass transport properties including oxygen diffusivity, oxygen permeability and water sorptivity of spacer-concrete composites at different ages are listed in Table 6.7. Compared to the 28d results of concrete samples with the same w/c ratio of 0.4 and embedded commercial cementitious spacers (shown in Table 5.2), most fibre-reinforced spacer-concrete composites showed lower mass transport properties at the same age. This indicates the potential of reducing mass transport by producing spacers with exposed fibres. However, it is worth noting that the comparison takes no consideration of the different volume fraction of the spacers, and therefore could overestimate the effectiveness of the new developed spacers.

Results of each property were normalised to the respective values from samples with the control composite sample (F-M), as shown in Figure 6.14. Most samples had normalised values below 1, which shows a decrease in mass transport when using fibre-reinforced spacers. This could be due to a combined improvements from the spacer and the spacer-concrete interface.

Table 6.7 Mass transport properties of fibre-reinforced spacer-concrete composite samples

Mass transport properties	Curing time (d)	7		28		365	
	Spacer	Flat	Split	Flat	Split	Flat	Split
Diffusivity ($\times 10^{-8} \text{ m}^2/\text{s}$)	M	12.11 (0.18)	9.90 (0.03)	10.09 (0.03)	8.13 (0.02)	5.77 (0.15)	3.23 (0.07)
	SF-12(0.5)	11.83 (0.17)	10.76 (0.27)	9.56 (0.07)	8.29 (0.05)	5.01 (0.06)	3.22 (0.07)
	SF-12(1)	11.98 (0.25)	10.54 (0.22)	9.73 (0.08)	8.62 (0.22)	4.43 (0.03)	3.19 (0.04)
	SF-25(1)	10.88 (0.03)	9.06 (0.12)	9.30 (0.12)	7.66 (0.11)	4.48 (0.01)	2.75 (0.03)
	GF-12(0.5)	12.98 (0.18)	11.20 (0.24)	11.53 (0.08)	9.73 (0.17)	3.74 (0.05)	2.75 (0.08)
	GF-12(1)	10.49 (0.03)	9.02 (0.14)	9.28 (0.10)	8.11 (0.11)	3.25 (0.02)	2.70 (0.08)
	PPF-12(0.5)	10.06 (0.12)	7.85 (0.24)	7.77 (0.10)	5.77 (0.19)	4.78 (0.04)	1.78 (0.05)
	PPF-12(1)	11.48 (0.22)	9.17 (0.20)	8.40 (0.10)	6.27 (0.16)	4.82 (0.09)	1.99 (0.05)
Permeability ($\times 10^{-17} \text{ m}^2$)	M	12.10 (0.90)	9.94 (0.10)	10.33 (0.36)	7.53 (0.06)	4.75 (0.09)	2.50 (0.75)
	SF-12(0.5)	13.10 (0.58)	7.34 (0.22)	10.26 (0.18)	4.83 (0.08)	2.12 (0.02)	0.81 (0.01)
	SF-12(1)	11.63 (0.96)	6.51 (0.14)	8.35 (0.03)	4.07 (0.10)	1.82 (0.06)	0.67 (0.01)
	SF-25(1)	6.73 (0.07)	4.29 (0.13)	6.33 (0.05)	3.66 (0.10)	1.24 (0.11)	0.58 (0.01)
	GF-12(0.5)	8.75 (0.06)	5.78 (0.10)	8.23 (0.05)	3.23 (0.06)	1.31 (0.02)	0.46 (0.03)
	GF-12(1)	5.73 (0.06)	3.14 (0.07)	5.65 (0.11)	1.92 (0.02)	1.66 (0.03)	0.34 (0.01)
	PPF-12(0.5)	4.51 (0.02)	2.17 (0.08)	3.97 (0.11)	1.20 (0.06)	4.02 (0.06)	0.51 (0.01)
	PPF-12(1)	6.07 (0.03)	5.15 (0.11)	5.44 (0.07)	4.14 (0.04)	1.09 (0.03)	0.66 (0.02)
Sorptivity ($\text{g}/\text{m}^2\text{min}^{0.5}$)	M	126.13 (3.88)	106.22 (4.70)	106.40 (5.03)	85.70 (5.81)	35.51 (2.10)	25.43 (1.90)
	SF-12(0.5)	119.90 (8.03)	107.12 (4.02)	105.76 (4.12)	91.73 (1.77)	21.17 (1.91)	15.43 (3.91)
	SF-12(1)	118.13 (2.18)	102.24 (2.65)	102.27 (4.01)	86.43 (0.74)	25.92 (5.60)	20.64 (1.33)
	SF-25(1)	109.05 (6.75)	93.87 (2.72)	91.42 (4.20)	77.56 (2.18)	25.17 (2.99)	18.21 (2.18)
	GF-12(0.5)	169.40 (8.78)	152.87 (5.72)	82.84 (11.63)	68.92 (9.75)	32.38 (18.60)	25.55 (0.41)
	GF-12(1)	113.53 (4.00)	104.60 (2.08)	102.32 (1.01)	87.69 (6.45)	19.12 (0.50)	15.40 (3.73)
	PPF-12(0.5)	105.31 (1.40)	80.33 (2.45)	75.91 (4.33)	55.94 (6.01)	17.08 (2.57)	5.63 (0.34)
	PPF-12(1)	116.61 (1.94)	92.45 (3.41)	84.64 (4.74)	65.30 (2.41)	20.33 (0.40)	11.16 (1.51)

Note: Standard deviation is indicated in brackets.

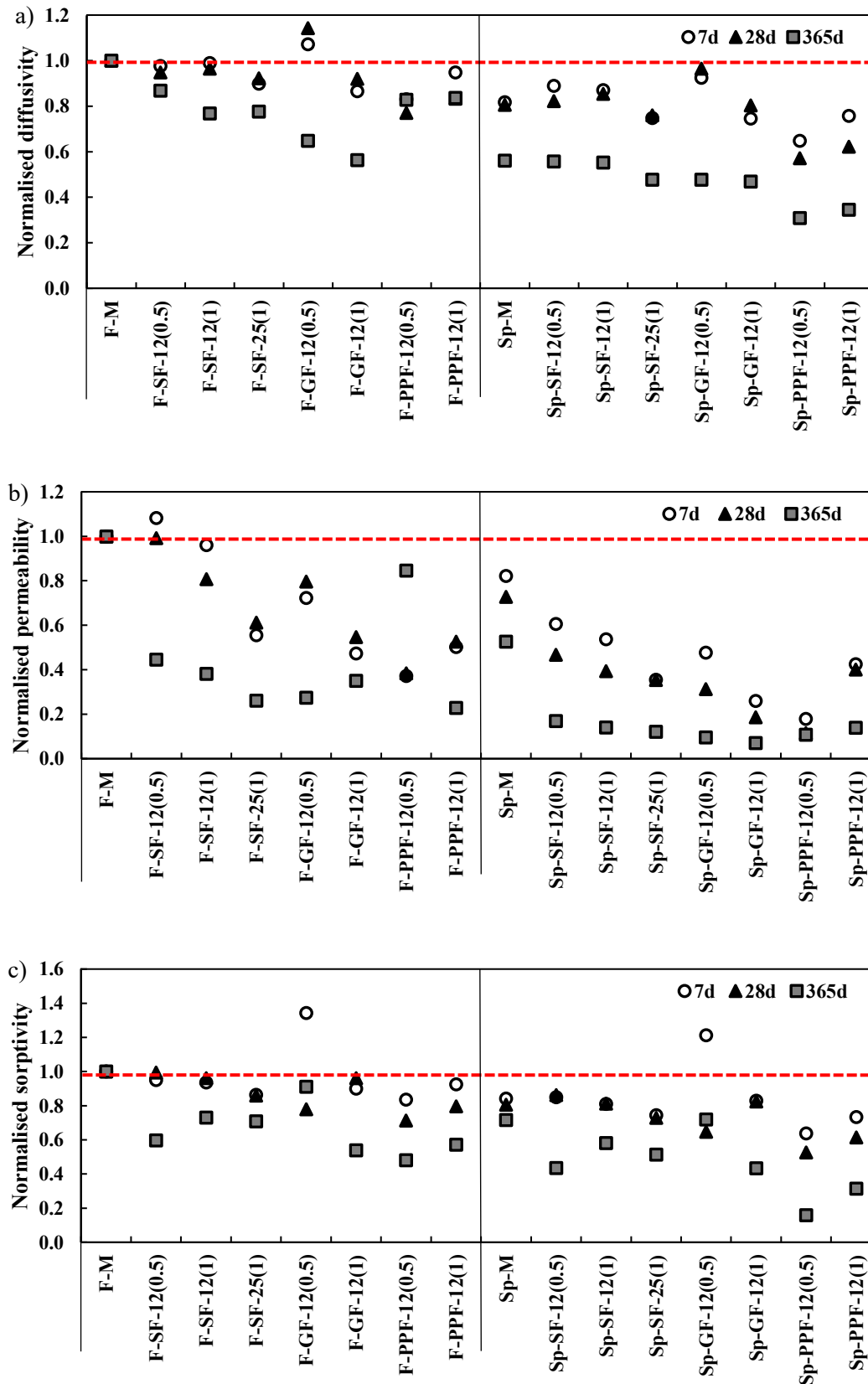


Figure 6.14 Normalised mass transport properties of fibre-reinforced spacer-concrete composites: a) diffusivity; b) permeability; c) sorptivity. The data is normalised to the respective values from the control composite sample (F-M) at same age

For samples with flat spacers, the normalised transport values showed inconsistent trends with curing age and composition of the spacers. These ranged between 0.56-0.99, 0.23-0.99 and 0.48-0.99 for diffusivity, permeability and sorptivity respectively. The reduction in mass transport is due to the lower transport properties of the spacers as shown in Chapter 6.3.1. However, there were some exceptions to this, for example samples with spacers GF-12(0.5) and SF-12(0.5), which gave higher transport at 7d. This could be due to the experimental error.

Samples with split spacers showed consistently lower mass transport compared to samples with flat spacers of the same composition and age. The difference increased with curing age. At 365d, the differences between split spacer-concrete composite and composite samples with flat spacers of the same composition ranged between 0.09-0.52, 0.09-0.74, and 0.10-0.32 for diffusivity, permeability and sorptivity respectively. This shows the efficiency of exposing fibres and unreacted cement particles on the surface of spacers through the proposed method in improving the microstructure of the spacer-concrete interface.

It is notable that the normalised transport values of samples with fibre-reinforced split spacers were generally lower than the respective control samples with mortar split spacers, especially at the later ages. The most obvious difference could be found in terms of permeability. At 365d, the normalised permeability for samples with mortar split spacer was 0.53, while the values for samples with fibre-reinforced split spacers ranged between 0.07-0.17. This represents a substantial benefit because previous research from Muslim et al. (2021b), Alzyoud et al. (2016) and Chapter 5.3.1 have shown that permeability was increased to the highest extent by the inclusion of spacers.

For samples with fibre-reinforced split spacers, the normalised transport values generally decreased with the increase in fibre volume of SF and GF within 28d of curing. However, a reversed trend could be seen for PPF. For diffusivity and permeability, the differences induced by fibre volume fraction became marginal at later ages. Fibres at their optimal volume fractions used in this study was compared to analyse the efficiency of different types of fibres. To be more specific, samples with split spacers made of SF-12(1), SF-25(1), GF-12(1) and PPF-12(0.5) were compared. PPF was found to be most effective while SF-12 was the least effective regardless of curing age and the tested properties. SF-25 was more effective for decreasing diffusivity and sorptivity after short-term curing, but the effectiveness could be surpassed by GF after longer-time curing. The effectiveness of PPF (at appropriate dosage) could be attributed to its pore refinement effects in the spacer and at the spacer-concrete interface. This

on the one hand reduces the pore size and connectivity, on the other hand hinders propagation of microcracks. The effectiveness of SF, particularly of short length (12mm), is suspected to be limited by the volume fraction used in this study.

6.3.4 Fluorescent epoxy impregnation

Cross-sections of spacer-concrete composite samples impregnated with fluorescent epoxy are shown in Figure 6.15. The impregnation depth (D_{IT}) at spacer-concrete interface was measured through image analysis and presented in Table 6.8 by increasing order of penetration. A clear penetration of the fluorescent epoxy could be seen through the spacer-concrete interface of the control sample (F-M), where the epoxy penetrated more than half-way through the interface. A much shallower penetration of 12.6 mm was observed for the sample with split spacer made of pure mortar (Sp-M), which shows the benefits of the proposed method for producing spacers. This reduction in epoxy penetration could be attributed to improvement in microstructure as a result of further hydration of the exposed cement particles and additional bonding generated from the surface roughness of the split spacers.

All samples with fibre-reinforced split spacers (except PPF-12(1)) showed further decrease in penetration depth through the spacer-concrete interface to within 8 mm. This is a clear improvement compared to the thorough impregnation commonly occurred at the commercial spacer-concrete interface. It is also worth noting that limited epoxy penetration occurred within the spacer part of these samples, and no obvious cracks were observed within the spacer either. This is important because the splitting method for preparing spacers could generate additional cracks, which could be detrimental to mass transport properties. Fortunately, the data suggest that the spacer preparation method did not induce additional damages.

However, the sample with PPF-12(1) spacer showed uncharacteristically high penetration depth at the spacer-concrete interface, and signs of epoxy penetrating the spacer through cracks (Figure 6.15h). This is consistent with the earlier observation of unusually high mass transport properties for samples with PPF-12(1) spacers (Figure 6.14). The cracks within the spacer could be generated during the splitting process and could be attributed to the increased ductility of the spacer when using high volume of fibres. Additionally, PPF has a tendency to clump and it was difficult to distribute the fibres homogeneously within the spacer, especially at a high fibre dosage. The unevenly distributed PPF could possibly lead to non-uniform strength within

the spacer as well as causing stress concentrations at certain localised regions during splitting of the spacer.

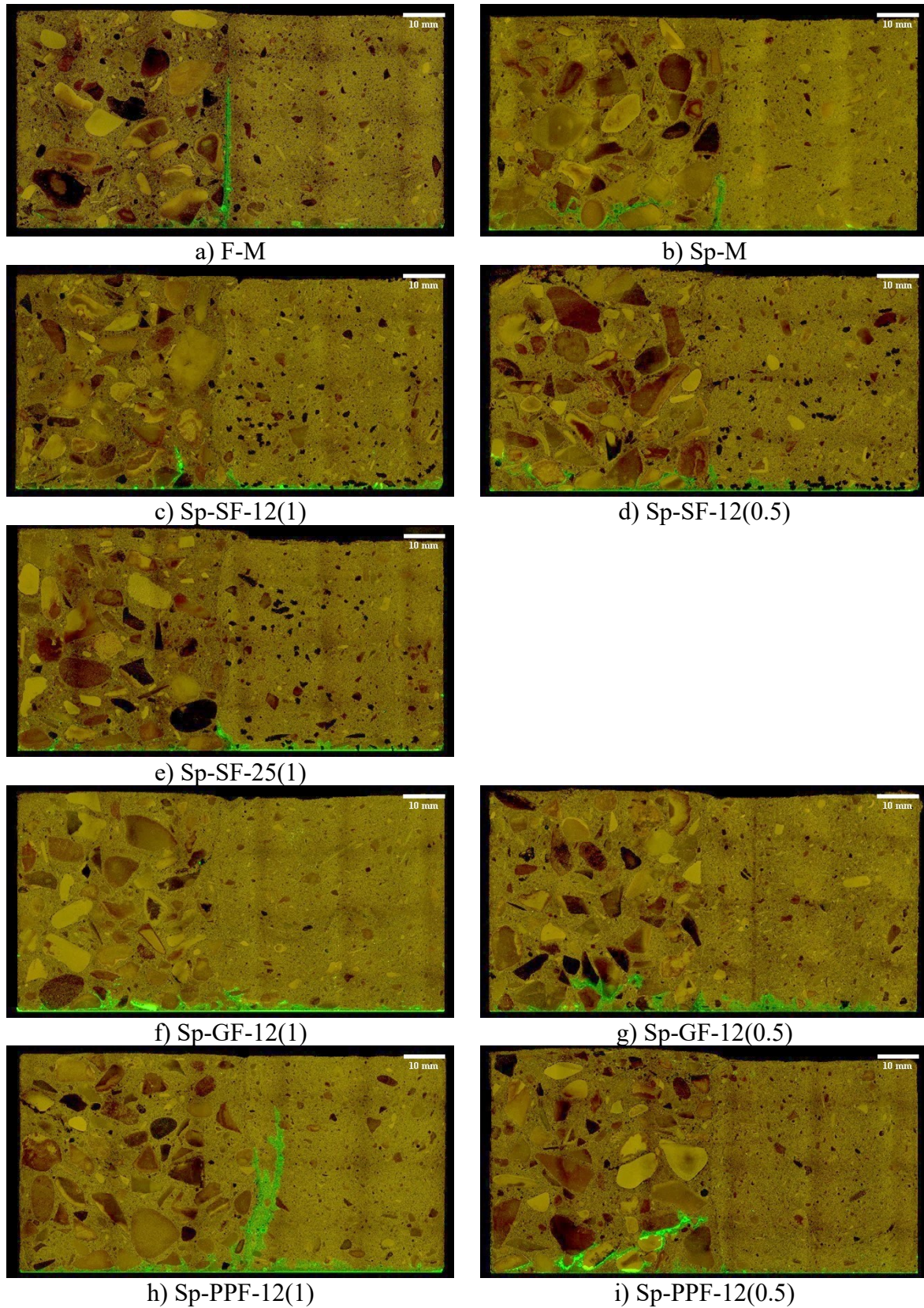


Figure 6.15 Cross-sections showing fluorescent epoxy impregnation at the fibre-reinforced spacer-concrete interface

Table 6.8 Impregnation depth at spacer-concrete interface

Sample ID	D _{IT} (mm)
Sp-PPF-12(0.5)	2.51
Sp-SF-12(1)	4.37
Sp-GF-12(0.5)	5.01
Sp-GF-12(1)	5.67
Sp-SF-12(0.5)	6.26
Sp-SF-25(1)	7.32
Sp-M	12.57
Sp-PPF-12(1)	29.52
F-M	37.21

6.3.5 Microstructure of spacer-concrete interface

Microstructure of the interface between fibre-reinforced split spacers and concrete was investigated through BSE imaging. The investigation aimed at better understanding the effects induced by different fibres. Thus, samples with optimal fibre volume fractions for each type of fibre were imaged, including Sp-SF-12(1), Sp-SF-25(1), Sp-GF-12(1) and Sp-PPF-12(0.5).

Sample preparation for electron microscopy was challenging for several reasons. The first difficulty was in locating fibres that cut across the spacer-concrete interface and maintaining these through the preparation process. Furthermore, there is a limitation on the maximum size of the samples prepared for BSE imaging as restricted by the equipment. This added the difficulty of exposing fibres within such a small area, especially across the interface. Fibres were randomly distributed in three-dimensions and those with their length parallel to the sample surface are ideal for imaging. However, this was difficult to achieve in practice and the high-speed diamond cutter could chip off these fibres. Another challenge was related to the grinding and polishing process. Both the spacer and concrete were composed of phases with different hardness, which could lead to an uneven grinding through the prepared surface known as surface relief. Therefore the samples were ground and polished carefully, and monitored with optical microscopy at every preparation stage, to avoid overgrinding and other defects.

SF were the most challenging to be detected across the spacer-concrete interface since very few steel fibres were exposed on the surface of the split spacer as reported in Figure 6.8. As shown in Figure 6.16, areas around SF were not well prepared due to the high hardness of steel

affecting the grinding and polishing of the surrounding cement paste. However, some interesting observations were made through imaging other parts of the spacer-concrete interface. For example, Figure 6.17a shows several short microcracks along the spacer-concrete interface, especially within the SF-12(1) spacer. Less microcracking were observed in the sample with SF-25(1) spacer and this could explain the decreased in mass transport when using longer SF. These microcracks are likely to be generated during the splitting of the spacer or shrinkage of the concrete when subjected to drying.

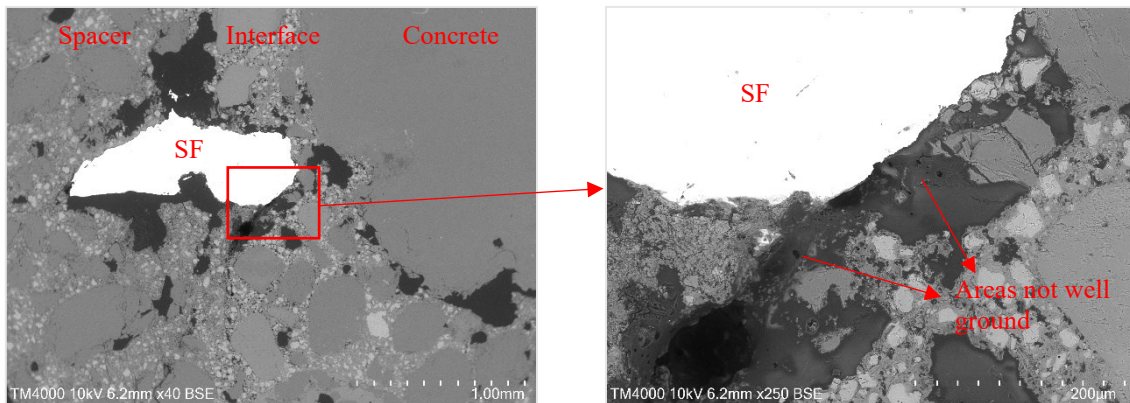


Figure 6.16 Difficulties in grinding areas around SF (spacer of SF-12(1))

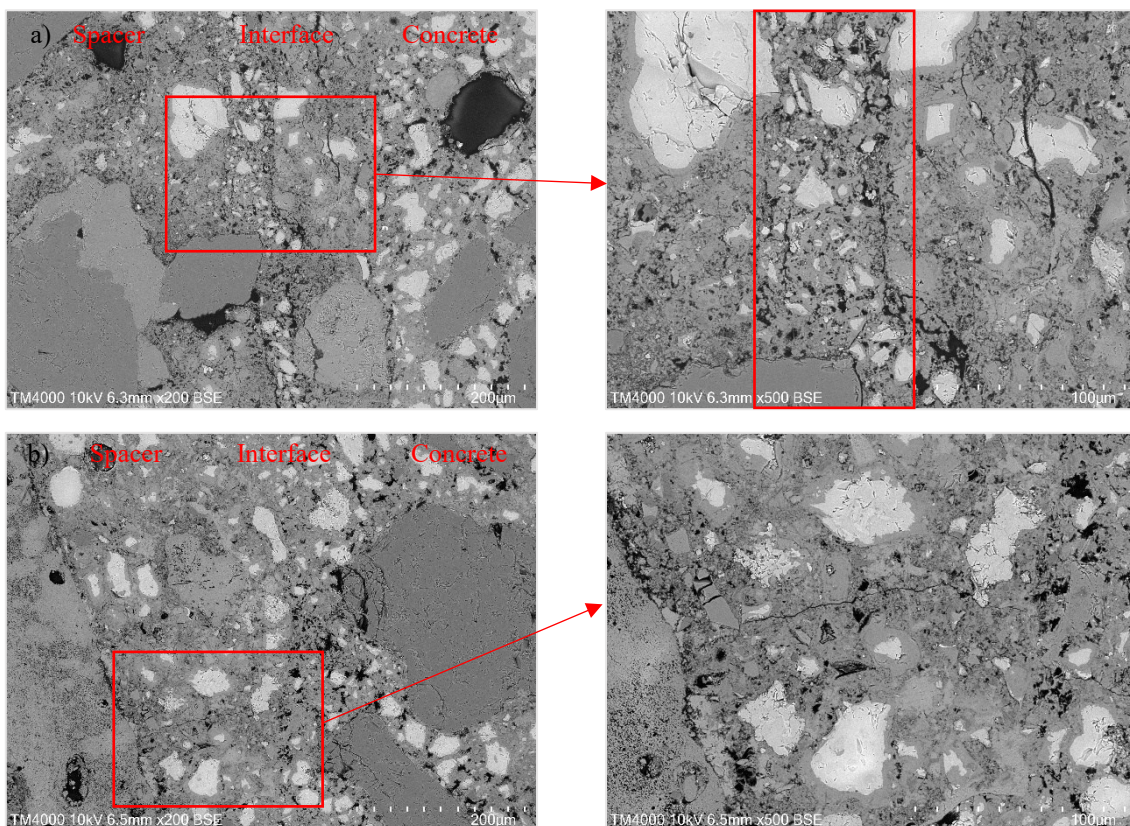


Figure 6.17 Spacer-concrete interface with split spacers containing: a) SF-12(1); b) SF-25(1)

Figure 6.18 shows examples of spacer-concrete interface microstructure containing GF, where the fibres are either aligned in the direction of the imaging plane or perpendicular to it. It can be seen that the fibres are oval shaped and occur in bundles, unlike SF. No obvious microcracks were observed around the GF, especially inside the spacer. The cement paste matrix was also found to be well bonded around and along the length of the GF, which are critical for enhancing the overall bond strength between the spacer and concrete. Good bonding between GF and the surrounding cement matrix will help to improve the bridging effects and therefore lead to increased bond strength compared to samples made of mortar without fibres. However, cross-section of the GF bundles shows voidage between individual fibre strands which were not subsequently filled with cement or hydration products. This could increase the local mass transport along the length of the fibres, and this might be a factor restricting the efficiency of using GF. However, the orientation of fibres was not controlled in this investigation and this aspect could be studied in future work.

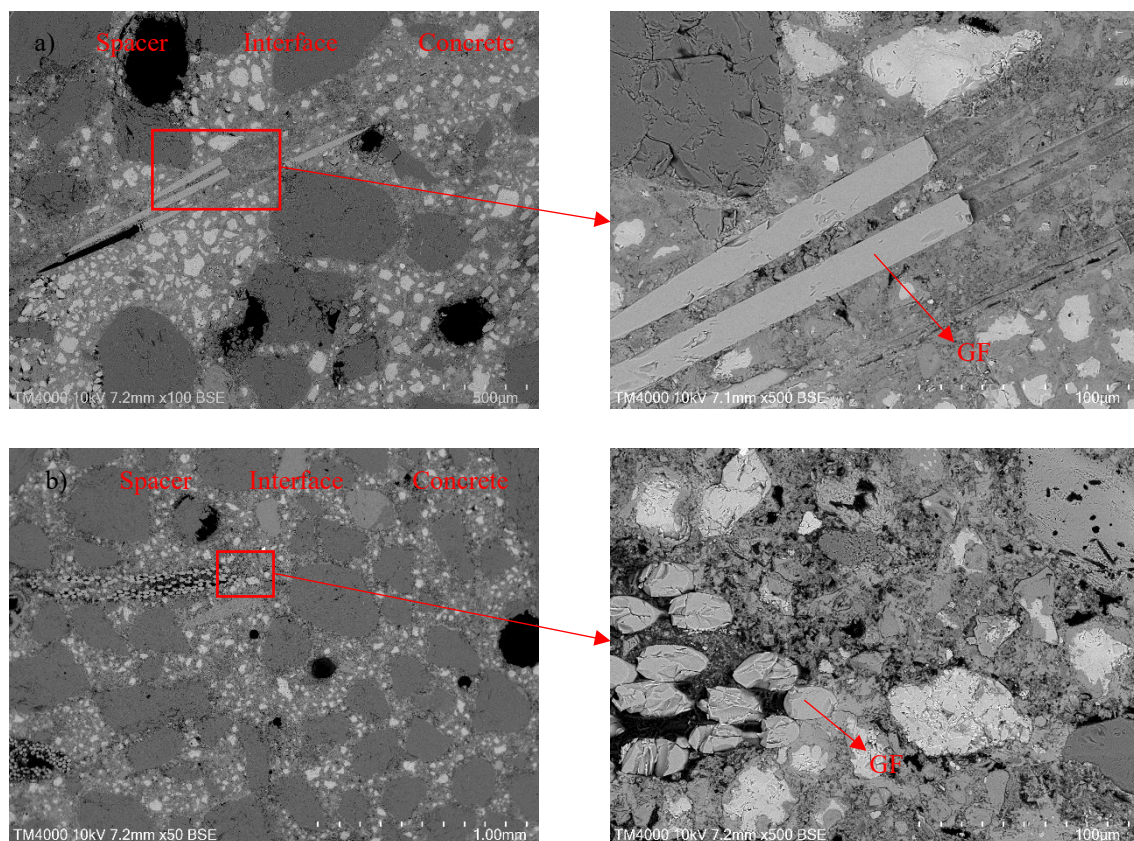


Figure 6.18 Spacer-concrete interface with spacer containing GF-12(1): a) parallel; b) perpendicular to the imaging plane

The interface between concrete and split spacer containing PPF-12(0.5) was found to be dense with low porosity, as shown in Figure 6.19. Very few micro-cracks were observed occasionally, which are likely induced by the specimen cutting, drying or preparation process. It is interesting to note the PPF filaments that bridged over on the concrete side with dense cement paste microstructure around the fibres. The refinement of the pore structure and lack of microcracking could explain the decreased mass transport properties of samples with PPF-12(0.5) spacers.

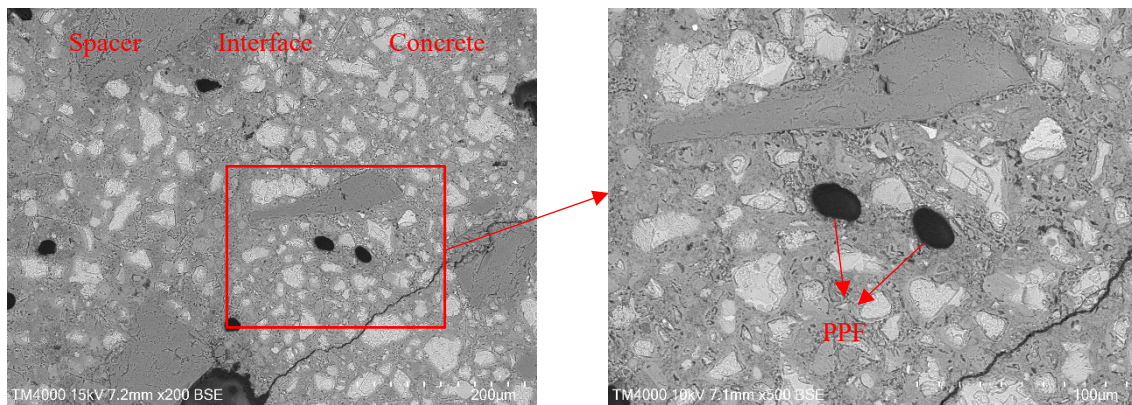


Figure 6.19 Spacer-concrete interface with spacer containing PPF-12(0.5)

Overall, the BSE imaging work found a very dense spacer-concrete interface occurring in all samples containing fibre-reinforced split spacers. In fact, locating the exact position of the interface was challenging in many cases due to the lack of distinctive features between the spacer and concrete. This is in contrast to the interface between commercial spacers and concrete, as reported in Chapter 5. It is also worth mentioning that all the samples were conditioned at 50°C, which is a relatively harsh drying regime that could induce shrinkage and thermal cracking, especially at the spacer-concrete interface. Compared to the cementitious spacer-concrete interface from samples conditioned at same regime from previous research as shown in Figure 6.20, a clear improvement on the microstructure could be found in this study. This is attributed to the combined benefits brought by the inclusion of exposed fibres, surface roughness and unreacted cement particles, produced by the proposed method.

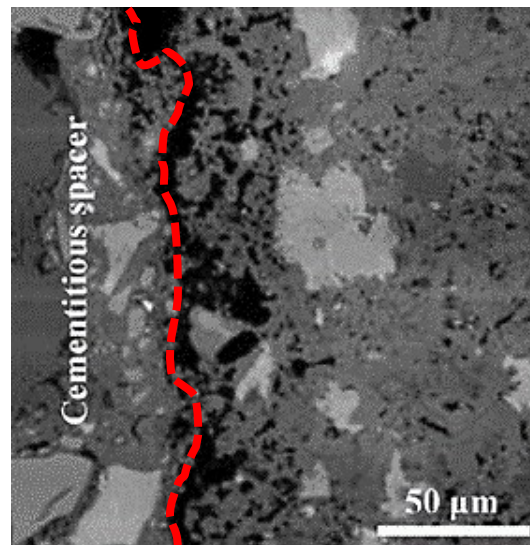


Figure 6.20 Porous interface between commercial cementitious spacer and concrete from previous research (Alzyoud et al., 2016)

6.4 Conclusions

This chapter presents an investigation on developing fibre-reinforced cementitious spacers which could help improve the spacer-concrete interface microstructural characteristics, bonding and mass transport properties of the concrete cover. Three types of fibres (steel, glass and polypropylene) with two lengths (12 and 25 mm) were used at two volume fractions (0.5% and 1%) to prepare the spacers. A new developed method was established for producing split spacers with exposed fibres, unreacted cement particles and surface roughness in order to enhance the bond between spacer and concrete. The developed split spacers containing exposed fibres were found to be highly effective in enhancing the bond strength and resistance against mass transport at the spacer-concrete interface. When compared to flat spacers of the same mix compositions, fibre-reinforced split spacers were found to be more efficient in terms of increasing bond strength and decreasing mass transport properties, in particular permeability. In addition, fibre-reinforced split spacers improved ductility and resistance to cracking when subjected to tensile stress. The level of improvement was dependent on the fibre type and dosage, length and the number of fibres exposed on the spacers. Scanning electron microscopy showed that fibre-reinforced split spacers were higher effective in producing a dense spacer-concrete interface microstructure with very little evidence of microcracking compared to conventional spacers.

Chapter 7 Cementitious spacers with reactive surfaces

This chapter aims to develop novel cementitious spacers with reactive surfaces that could undergo chemical reactions with freshly cast concrete, and thereby improving the microstructure, bonding and mass transport properties at the spacer-concrete interface. An example of this was achieved by using low Portland cement (PC) content and high amounts of ground granulated blast furnace slag (GGBS) as an alternative binder in spacers. GGBS have much lower hydration rate compared to Portland cement and they react in the presence of alkalis, thus have a high potential to induce surface reactivity when cast in concrete. Spacers with different water/binder (w/b) ratios and slag replacement ratios were produced. Their performance and bonding behaviour with concrete were evaluated at a range of curing ages.

7.1 Introduction

Ground granulated blast-furnace slag (GGBS) is an industry by-product generated from the smelting of raw ore. The major components include CaO , SiO_2 , Al_2O_3 and MgO , which are the same as Portland cement (PC), but in different proportions. The hydraulic reactivity of GGBS is highly dependent on its composition, especially the basicity, defined by indices such as CaO/SiO_2 (Cabrera et al., 2012) and $(\text{CaO}+\text{MgO})/(\text{SiO}_2+\text{Al}_2\text{O}_3)$ (Eissa et al., 2012). The more basic it is, the higher the hydraulic activity. GGBS with a basic coefficient higher than 1 is commonly used as a replacement for Portland cement.

Two-phase reactions occur during the hydration of GGBS-blended cement, primarily with alkali (Na and K) hydroxide released and consequently with calcium hydroxide generated from the hydration of PC (ACI 233 R03, 2003). Therefore, the initial hydration of GGBS-blended cement is slower than pure Portland cement. Previous research (Brooks et al., 2000; Ramme, 1990; Alhozaimy et al., 2012; Güneyisi et al., 2008; Zhao et al., 2015; Robeyst et al., 2008) found that the initial and final setting times of concrete are prolonged in the presence of GGBS, and the effect increases at higher GGBS replacement levels. For example, the initial and final setting times was increased by a factor of 2.75 and 2.27 respectively at 60% replacement of GGBS (Gesouglu & Özbay, 2007).

Strength development of GGBS-based concrete is influenced by several mix design factors, e.g. substitution level of GGBS, w/b ratio, volume fraction of aggregates, curing condition,

testing age etc. The early-age compressive strength shows an inverse correlation to GGBS content, which is consistent with the slowing rate of hydration caused by the addition of GGBS. However, the early-age strength gain is also related to curing environment, especially the temperature and humidity (Barnett et al., 2006). The hydration process and strength development are accelerated at elevated temperature and humidity levels. Prolonged moist curing is especially important when using GGBS because at early ages, more capillary pores are formed due to the low initial hydration rate, which allows a greater water loss through evaporation and hinders subsequent hydration. Optimal replacement level of GGBS has been investigated in many studies and this is typically 50% to 60%. Inevitably, early strength is decreased but the 28d compressive strength increased by 30% to 45% (Neville, 2011). Higher substitution with GGBS will cause further reduction in compressive strength, especially at a high w/b ratio (Wang et al., 2013). Additionally, a remarkable rise in the workability, bleeding amount and rate occur when the replacement level is higher than 60%.

Compared to PC, blended cements containing GGBS generate a higher C-S-H and lower lime content after hydration, which cause refinement of the pore structure. For examples, previous studies (Daube, Jean ; Bakker, 1986) showed refinement in capillary pore size distribution and reduction in total porosity in GGBS-blended cement compared with pure PC. Johari et al. (Megat Johari et al., 2011) found a reduction of 29.32% in the 28d porosity when using 60% slag replacement while Jamshidi et al. (2015) observed that the porosity at 28d decreased by 18.96% and 10.34% at 50% and 70% slag replacement respective.

Consequently, mass transport properties such as permeability and water absorption also undergo reduction with incorporation of GGBS (Ling & Poon, 2014). Cheng et al. (2005) found that permeability of concrete decreased from 2.56×10^{-3} to 1.32×10^{-3} m/s by incorporating 60% slag at 28d. In addition, the age of testing has an obvious effect on permeability due to the pozzolanic reaction that occurs at much later ages. Al-Otaibi (2008) found that the incorporation of 60% slag resulted in permeability reduction of 33.73% and 61.9% at 7d and 182d, respectively. Güneyisi and Gesoglu (2008) tested concretes with varying amounts (0-80%) of slag and found that water absorption decreased with increasing slag content. Özbay et al. (2013) also observed a decreasing tendency in water absorption at 55%, 69% and 81% slag. Similarly, the incorporation of GGBS has a positive effect on the penetration resistance of chloride ion. The pozzolanic reaction of slag partially clogs the capillary pores and therefore reduces the penetration of chloride ions (Li & Roy, 1986).

However, the incorporation of GGBS can induce a negative effect on carbonation resistance due to the lower content of C-H after hydration (Younsi et al., 2013; Sisomphon & Franke, 2007; Borges et al., 2010; Gruyaert et al., 2013). Mixes with high GGBS contents are especially vulnerable to carbonation. Osborne (1999) tested the carbonation depth of slag-blended concrete after 5 years of exposure to an industrial environment. The measured carbonation depth was 1 to 1.5 mm for concrete with 50% slag and increased to 5 mm for concrete with 70% slag. Borges et al. (2010) studied the accelerated carbonation resistance of 75% and 90% GGBS blended pastes. Substantial carbonation depths were observed in samples containing slag, while the control PC paste showed no carbonation. However, a higher curing temperature (60°C) was found to lessen carbonation rate, which provides a reference for mitigating the low carbonation resistance of slag-blended systems.

Using GGBS as an alternative binder refines the pore structure and improves the durability of concrete, particularly at later ages. However, limited commercial cementitious spacers contained GGBS according to Chapter 4. Furthermore, GGBS have lower hydration reactivity than PC and could be activated in the presence of alkaline solution. Therefore, spacers with exposed unreacted GGBS particles are expected to generate better chemical bonding with concrete by reacting with the pore solution and C-H from concrete. Additionally, the consumption of water and C-H would also be beneficial in refining the microstructure at spacer-concrete interface. No research has been carried out on producing and characterising spacers with exposed unreacted cementitious particles (particularly GGBS). Therefore, in this chapter, four GGBS replacement ratios and two w/b ratios were investigated for producing spacers with reactive surfaces. A novel spacer producing method for exposing reactive cementitious particles was validated. The effect of the developed spacers on spacer-concrete bond strength, mass transport properties and microstructure were evaluated.

7.2 Experimental

7.2.1 Materials and mix proportions

The binders used in this chapter were GGBS (referred to as slag) and CEM I 52.5N. Their oxide compositions determined by XRF are listed in Table 7.1. Thames Valley sand (maximum size of 5 mm) and gravel (maximum size of 10 mm) were used as the fine and coarse aggregates. Their water absorption and moisture content were measured frequently and used to correct the

mix proportions prior to casting. MasterGlenium SKY 1901 was used as the superplasticizer for achieving sufficient workability.

Table 7.1 Oxide composition (% wt.) of binders used in this study

Binder	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	SO ₃
GGBS	41.5	34.7	11.5	0.5	6.1	0.7	0.2	2.9
CEM I	63.4	20.8	5.4	2.4	1.5	0.7	0.3	2.9

Mortars at two w/b ratios (0.35 and 0.40) and four slag replacement contents (0, 60%, 70% and 80% wt.) were used to produce spacers. Their mix proportions are shown in Table 7.2. Aggregate volume fraction was set as 50% for all mixes. Dosage of superplasticizer was determined through a series of trial mixes to ensure that the workability of all mixes meet the flow table test requirements according to BS EN 1015-3:1999(1999). Mix proportions were determined by absolute volume method. The naming convention of these mixes followed the rule of Sx(y), of which x represents the slag replacement ratio and y represents the w/b ratio. For example, S60(0.4) refers to the mortar spacer with 60% slag and w/b ratio of 0.4. The concrete used in this chapter was of the same composition as used in Chapter 6, this is shown in Table 7.3 for ease of reference.

Table 7.2 Mix proportions for slag-based spacers

Sample ID	Slag(kg/m ³)	Cement(kg/m ³)	Sand(kg/m ³)	Water(L/m ³)	Superplasticizer(L/m ³)
S0(0.4)	0	692.0	1193.7	281.6	2.1
S60(0.4)	415.2	276.8	1193.7	281.9	1.8
S70(0.4)	484.4	207.6	1193.7	282.0	1.6
S80(0.4)	553.6	138.4	1193.7	284.1	1.4
S0(0.35)	0	749.1	1193.7	264.5	5.7
S60(0.35)	449.5	299.6	1193.7	265.2	4.8
S70(0.35)	524.4	224.7	1193.7	265.6	4.2
S80(0.35)	599.3	149.8	1193.7	265.9	3.8

Table 7.3 Mix proportion for concrete

Mix ID	w/c ratio	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (L/m ³)	Superplasticizer (L/m ³)
C0.4	0.4	418.14	715.05	1073.64	175.06	2.66

7.2.2 Sample preparation

Composite cylindrical samples consisting of one half representing the mortar spacer and the other half representing concrete were prepared for this investigation. Two types of spacers were prepared: a) split spacers produced with the proposed method described in Chapter 3.2 to generate rough surface texture and expose unreacted cement, and; b) control spacers with flat cast surfaces that are similar to conventional spacers. Preparation of the composite spacer-concrete samples followed the same process as described in Chapter 6.2.2 and is summarised in Figure 7.1 for reference. The naming convention of the spacer-concrete composite samples follows the order of “type of spacer - material of spacer”, where “Sp” and “F” represent split spacer and flat spacer respectively. For example, Sp-S0(0.4) refers to the composite sample containing a split spacer with 0% slag at w/b ratio of 0.4. The half-cylindrical spacers were cured in a fog room (100% RH, 21°C) for 7d, and the spacer-concrete composite samples were subsequently cured (100% RH, 21°C) for 7d, 14d, 28d, 91d and 365d.

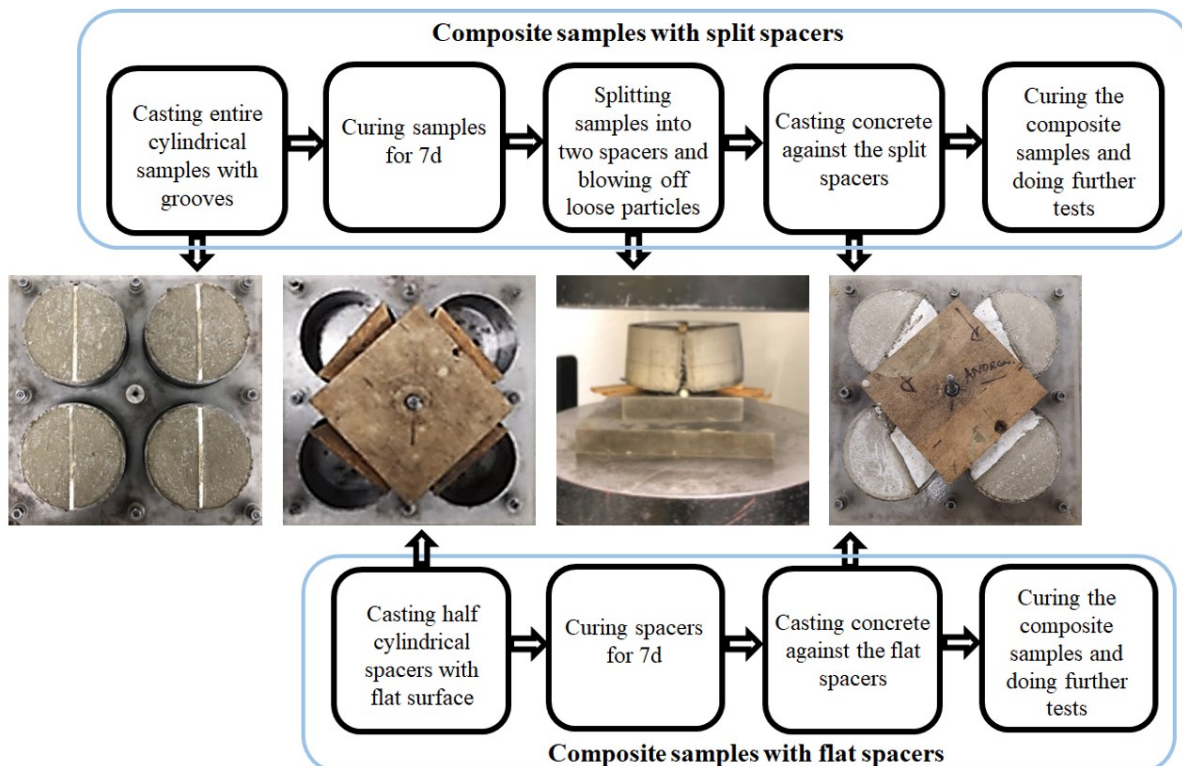


Figure 7.1 Preparation of spacer-concrete composite samples

7.2.3 Properties of slag-based cementitious spacers

The slag-based cementitious spacers were tested for compressive strength and mass transport properties. Three replicates were prepared for each test. Compressive strength was measured after curing for 7 and 28 days, for all the mix proportions listed in Table 7.2, on 50 mm cube specimens. Mass transport properties were investigated following the order of oxygen diffusivity, oxygen permeability and water sorptivity. These were carried out selected critical mixes, including S0(0.35), S60(0.35), S80(0.35), S0(0.4) and S80(0.4). The rationale for this selection will be explained in Chapter 7.3.1. The samples were cured in a fog room (100% RH, 21°C) for 7 and 28 days, and then conditioned at 50°C until constant mass before being tested. The tests were conducted following the procedures described in Chapter 3.4.

7.2.4 Properties of spacer-concrete composites

Tests carried out on the slag-based spacer-concrete composite samples included bond strength, mass transport, fluorescent epoxy impregnation, BSE imaging and accelerated carbonation. Details of curing, conditioning regime and number of replicates for each test are listed in Table 7.4. Details of the test procedures were described in Chapter 3 and therefore is omitted here. Accelerated carbonation was conducted by exposing samples to 3% CO₂ at 75% RH and 20°C for over 7 months, followed by sectioning and spraying phenolphthalein indicator on the middle cross-section perpendicular to the spacer-concrete interface. The depth of carbonation was determined by measuring the depth of colourless areas from the edge of the sample exposed to CO₂.

Table 7.4 Details of curing, conditioning and number of replicates for tests on spacer-concrete composite samples

Tests	Curing time (d)	Sample conditioning	Number of replicates
Bond strength	7; 14; 28; 91	-	4
Mass transport	7; 14; 28; 365	50°C oven	2 or 3
Fluorescent impregnation	7; 28	50°C oven	1
BSE imaging	7; 365	50°C oven	1
Accelerated carbonation	28	20°C, 75% RH conditioned; 3% CO ₂ carbonated for 224d	2

7.3 Results and discussion

7.3.1 Performance of slag-based spacers

The 7d and 28d compressive strength of the slag-based cementitious spacers are shown in Figure 7.2. As expected, compressive strength increased with decrease in w/b ratio and increase in curing time, for the same binder type. Using slag as an alternative binder decreases the 7d compressive strength at both w/b ratios, with a larger decrease occurring at higher slag replacement. This is due to the lower reactivity of slag and therefore a slower strength development at early ages compared to Portland cement. Slag replacement of 60% was optimal in terms of achieving the highest 28d compressive strength regardless of w/b ratio. Further increase in slag content led to a decrease in compressive strength relative to the control PC mix. This is because the slag pozzolanic reaction is limited by lack of C-H generated from cement hydration. Although the filler effect of slag may contribute to microstructure and strength development, this is clearly insufficient to compensate the aforementioned strength reduction.

Although using higher slag contents led to a reduction in strength, the 28d compressive strength values for all mixtures could meet the minimum requirement of 50 MPa for spacers as specified in BS 7973-1:2001 (2001). This lends support to the idea of developing slag-based spacers where a high content of unreacted slag particles on the exposed surface would react with freshly cast concrete. From this perspective, using lower w/b ratio and higher slag replacement would be more promising. Therefore, mixes S0(0.35), S60(0.35) and S80(0.35) were further investigated, while S70(0.35) was excluded because it showed marginal strength difference with S80(0.35). At w/b of 0.4, only the highest slag content of 80% slag was further studied and S0(0.4) was included as benchmark for comparison.

Mass transport properties of the selected mix proportions for further investigation are shown in Table 7.5. As expected, mixtures with lower w/b ratio and longer curing time had lower mass transport properties, which is attributed to their denser microstructure. Slag replacement at the designed proportions were beneficial for decreasing mass transport further by refinement of the pore structure. At w/b ratio of 0.35, slag replacement of 60% achieved the lowest mass transport properties. However, in contrast to compressive strength, increasing slag content from 60% to 80% only caused small differences to mass transport properties.

The 7d and 28d water sorptivity of the tested mix proportions were within the range of the results from the investigated commercial cementitious spacers (17.6 to 247.2 g/m²min^{0.5} according to Chapter 4.3.3). This is expected because it takes longer time for the slag-based mixtures to hydrate and therefore obtain lower mass transport properties, particularly at high slag replacement ratio. Therefore, the spacers developed in this chapter could obtain better resistance to mass transport at later ages. It is also worth noting that due to the lack of clear regulations on the durability of cementitious spacers, it is very difficult to define limiting values for the development of such spacers.

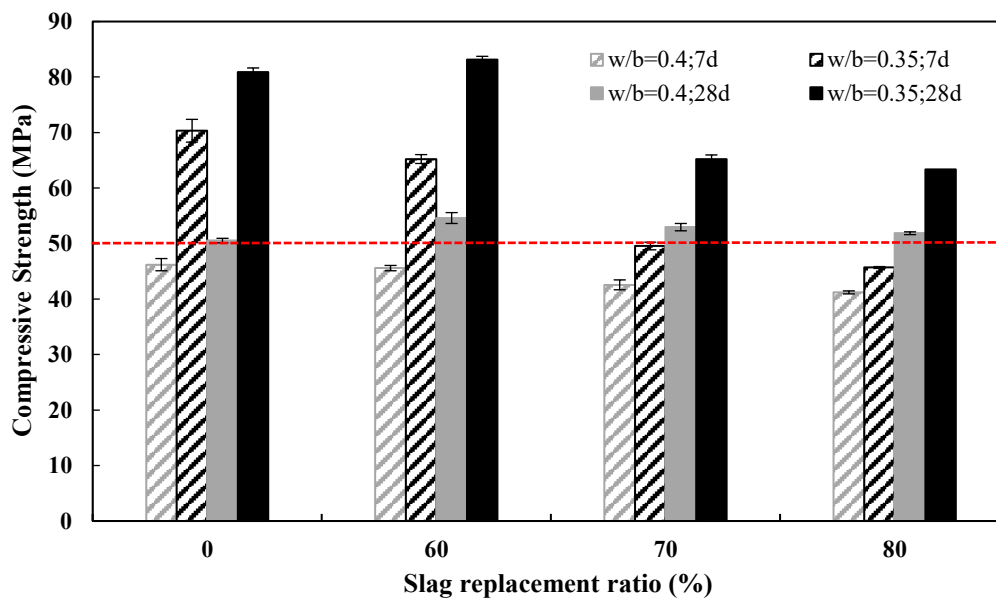


Figure 7.2 Compressive strength of slag-based spacers

Table 7.5 Mass transport properties of slag-based spacers

Sample ID	Diffusivity ($\times 10^{-8} \text{m}^2/\text{s}$)		Permeability ($\times 10^{-18} \text{m}^2$)		Sorptivity ($\text{g}/\text{m}^2 \text{min}^{0.5}$)	
	7d	28d	7d	28d	7d	28d
S0(0.4)	18.07 (0.07)	14.37 (0.26)	60.54 (1.01)	42.43 (1.99)	185.17 (9.95)	145.74 (12.42)
S80(0.4)	9.64 (0.48)	8.87 (0.18)	53.85 (1.69)	35.47 (1.21)	158.57 (2.72)	116.26 (1.67)
S0(0.35)	11.73 (0.25)	9.12 (0.38)	46.53 (1.39)	28.17 (1.77)	114.61 (5.68)	106.76 (9.27)
S60(0.35)	4.94 (0.05)	3.74 (0.03)	33.05 (1.49)	19.25 (1.38)	107.08 (0.89)	91.62 (1.59)
S80(0.35)	5.02 (0.02)	3.82 (0.02)	33.67 (1.24)	22.53 (1.61)	107.4 (2.67)	93.72 (3.08)

Note: Each value was obtained from the average of three replicates; Standard deviation is marked in the bracket.

7.3.2 Bond strength between reactive spacers and concrete

7.3.2.1 Bond strength

The relationship between bond strength and curing time is shown in Figure 7.3. Strength of cylindrical samples made of concrete (C0.4) is also presented for comparison. Each bond strength value is an average of four replicates and the error bars indicate the standard deviation. Detailed test results are listed in Appendix IV. The results show that bond strength increased with curing age. Most of the strength increase occurred from 7d to 14d, except for F-S0(0.4), F-S80(0.4) and F-S0(0.35). Beyond 28d, the bond strength remained relatively constant. This indicates that the bond between spacer and concrete developed mainly within the first 28d. The results also clearly show that the bond strength achieved with split spacers is substantially greater than that with flat spacers.

At equal w/b ratio, slag replacement had different effects on samples with split spacers and flat spacers. For samples with split spacers, bond strength decreased with increase in slag replacement at 7d, but the relation inversed after 14d. This can be explained from the bonding mechanism between split spacers and concrete, which is a combination of mechanical interlocking and chemical bonding. The former is attributed to filling of the spacer surface roughness with freshly-cast concrete, while the latter is induced by the reaction of the exposed unreacted binder. This includes hydration of unreacted cement, alkali-activation/hydration of unreacted slag, and pozzolanic reaction between slag and portlandite. Cement hydration and activation of the slag when exposed to alkaline pore solution from concrete is expected to be more rapid than pozzolanic reaction, and therefore play a dominant role in contributing early-age chemical bonding between spacer and concrete. Gradually, with generation of portlandite from cement hydration, any remaining slag particles may undergo pozzolanic reaction and contribute to additional chemical bonding. From 14d, the combined chemical reactions begin to have an obvious effect on bond strength, resulting in values surpassing those of samples without slag.

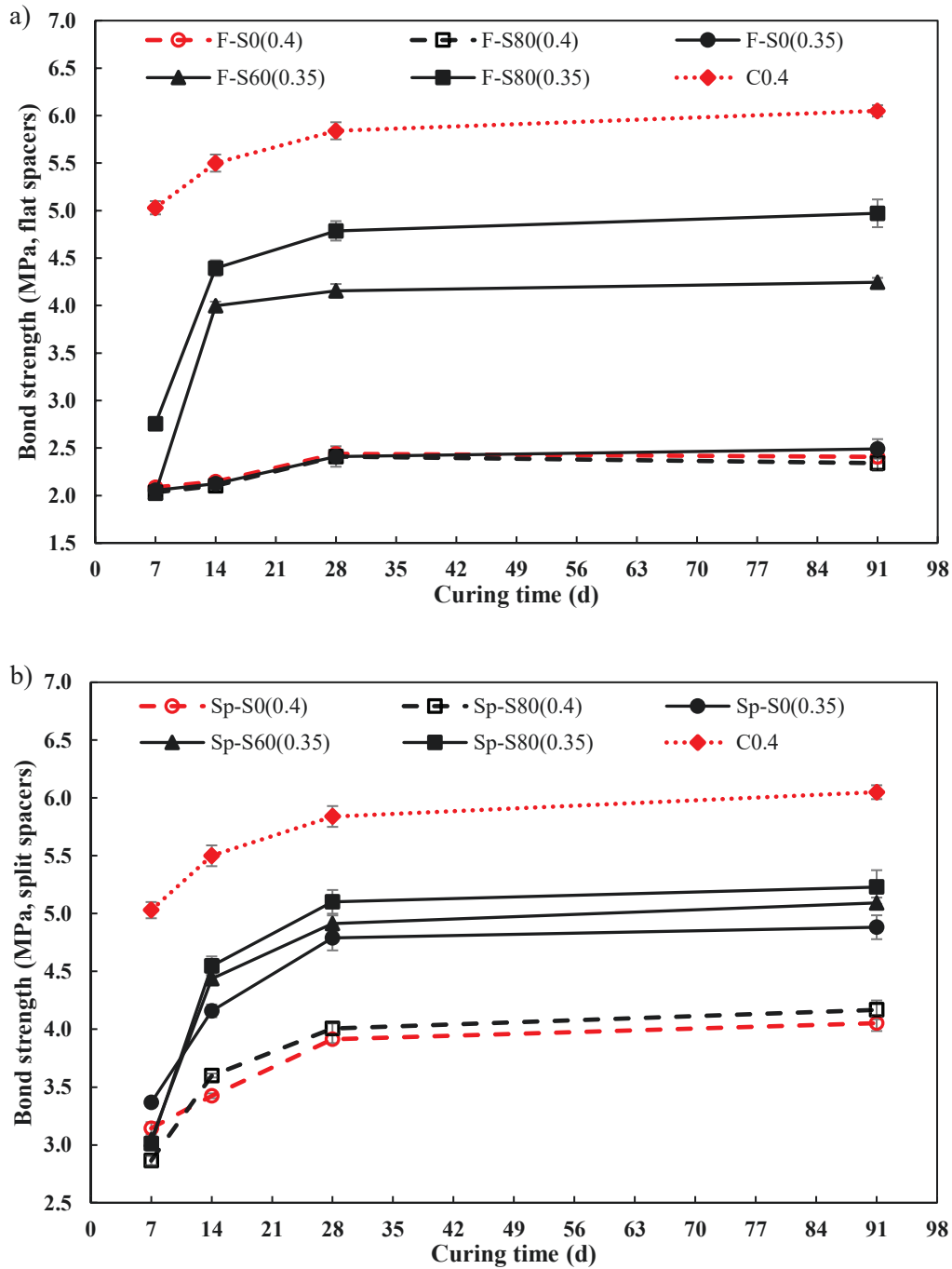


Figure 7.3 Bond strength of spacer-concrete composite samples with slag-based spacers: a) flat spacers; b) split spacers

For samples with flat spacers at w/b ratio of 0.35, bond strength showed a positive correlation with slag content at all ages. This suggests that even when mechanical interlocking is weak, the chemical bonding induced by activating the unreacted slag particles within the near-to-surface zone of the spacer, either through alkali-activation, hydration or pozzolanic reaction, is sufficient to induce a positive effect. Spacers with 80% slag had the highest potential for such

chemical bonding to occur, as reflected in the bond strength results. In contrast, samples with flat spacers at w/b ratio of 0.4 showed marginal differences in bond strength between 0 and 80% slag. This is related to the greater degree of hydration at higher w/b ratio leaving less unreacted cementitious particles on the spacer surface. Therefore, only limited chemical bonding could be generated.

When comparing equal slag content, samples with split spacers consistently showed higher bond strengths than that of flat spacers at all ages. This shows that the splitting method is effective in exposing unreacted particles for further reaction and the generated surface roughness is beneficial for promoting mechanical interlocking. For samples with split spacers at w/b ratio of 0.35, bond strength surpassed 75% the strength of entire concrete samples (C0.4) after 14d. At 28d, bond strength ratios to that of the entire concrete samples (C0.4) reached 82%, 84% and 87% for samples with 0% (Sp-S0(0.35)), 60% (Sp-S60(0.35)) and 80% (Sp-S80(0.35)) slag respectively. This indicates the effective bond generated between the split spacers with reactive surfaces (particularly at low w/b ratio and with high slag content) and concrete. One reason restricting the effectiveness of such split spacers is the grooves introduced during spacer production. The pre-introduced grooves on spacer were subsequently filled with concrete when preparing the composite samples. These areas account approximately 13% the interfacial cross-section area, where no unreacted particles could be exposed for chemical reaction. Additionally, a discontinuity at these positions may lead to stress concentrations and damages near these areas.

Figure 7.4 shows the normalised bond strength of spacer-concrete composites benchmarked with the respective results of control sample F-S0(0.4), which has a commonly used w/b ratio and similar surface type as commercial spacers. The control sample is the same as used in Chapter 6 (nominated as F-M). Compared to the control sample, an obvious increase in bond strength (by a factor of 1.34 to 2.12) was observed especially after 14d curing for all samples except F-S0(0.35) and F-S80(0.4). Higher increment in bond strength was found when using higher slag replacement and lower w/b ratio combined with the splitting method. For example, the bond strength was doubled only after 14d curing when using split spacers with 60% and 80% slag at w/b ratio of 0.35.

At equal w/b ratio (0.4), split spacers with 80% slag showed lower effectiveness in improving bond strength with concrete (compared to the control sample) than all split spacers with fibre reinforcement developed in Chapter 6 (results shown in Figure 6.6b) at 7d. This is not

surprising because the chemical reactions between the split spacers with high slag contents and the concrete is slow and thereby would limit the bond strength development at early age. After 14d, the effectiveness of split spacers with 80% slag was highly improved but still below that of split spacers reinforced with steel fibres, irrespective of the fibre length and volume fraction.

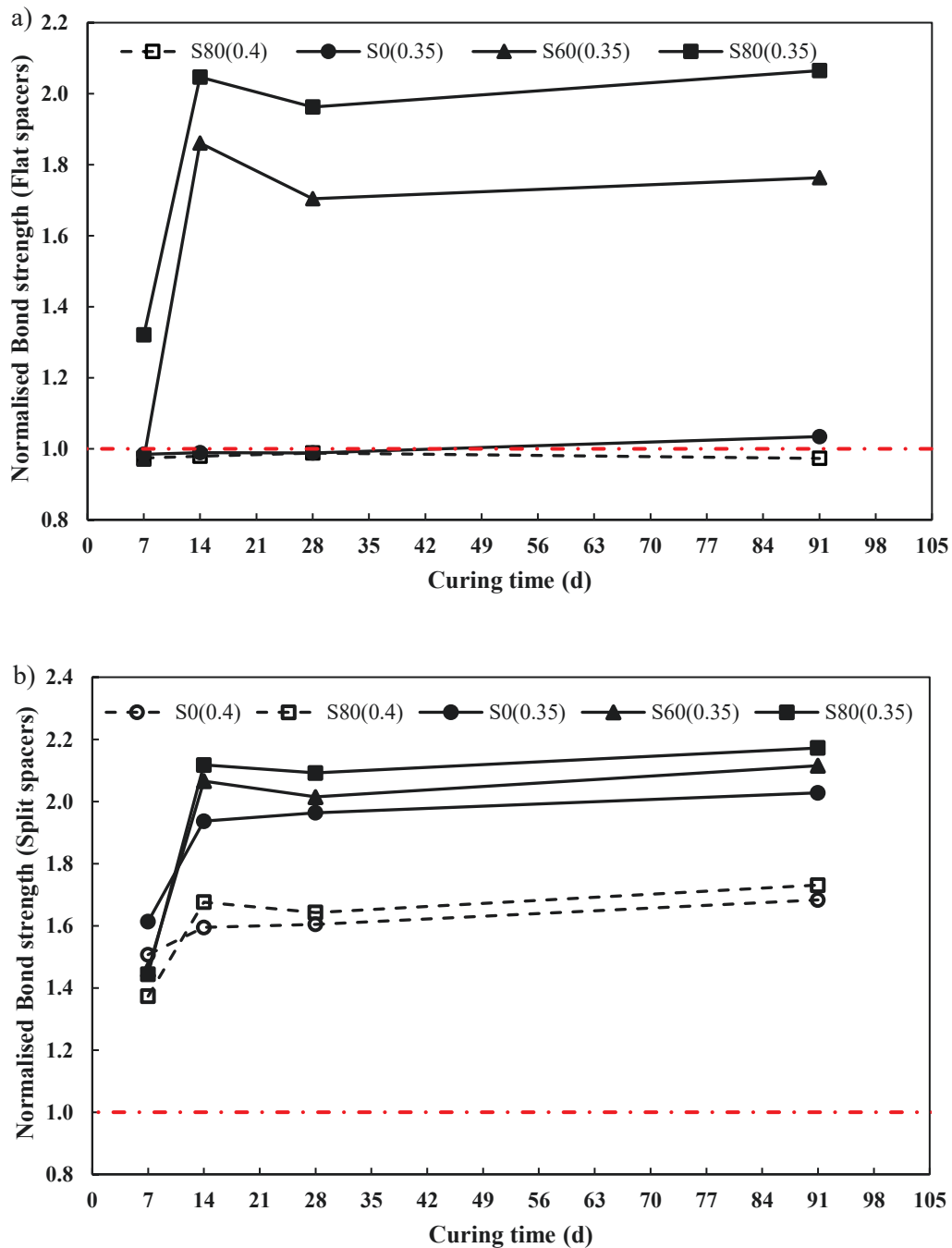


Figure 7.4 Normalised bond strength of spacer-concrete composites with slag-based spacers: a) flat spacers; b) split spacers. The data is normalized to bond strength of the control composite sample (F-S0(0.4)) at respective age

7.3.2.2 Typical failure modes

Upon splitting the spacer-concrete composite samples, the fractured surface was examined to ascertain the type of failure that has occurred. The observed failure mechanisms could be divided into three main categories: de-bonding (DB), fracturing of the spacer (FS) and fracturing of the concrete (FC). Examples of these are shown in Figure 7.5. DB is confirmed when a clean (smooth) separation of the spacer-concrete interface occurred without fracturing of either the spacer or concrete. FS and FC are confirmed by obvious damages (fracturing) that occurred either on the spacer or concrete respective. The failure modes of the tested samples at different curing ages are summarised in Table 7.6. Generally, most of the samples containing flat spacers failed by de-bonding only as expected. Samples containing split spacers failed by a combination of mechanisms.

Samples with split spacers mainly failed through fracturing of the spacer-concrete interface. In contrast, samples with flat spacers failed mainly through de-bonding of the interface. This suggests that the surface condition of the spacer influences the interface bond between spacer and concrete. The splitting procedure used in making spacers appear to be effective in generating additional surface roughness while exposing fresh unreacted cementitious, therefore encouraging a combination of chemical bonding and mechanical interlocking.

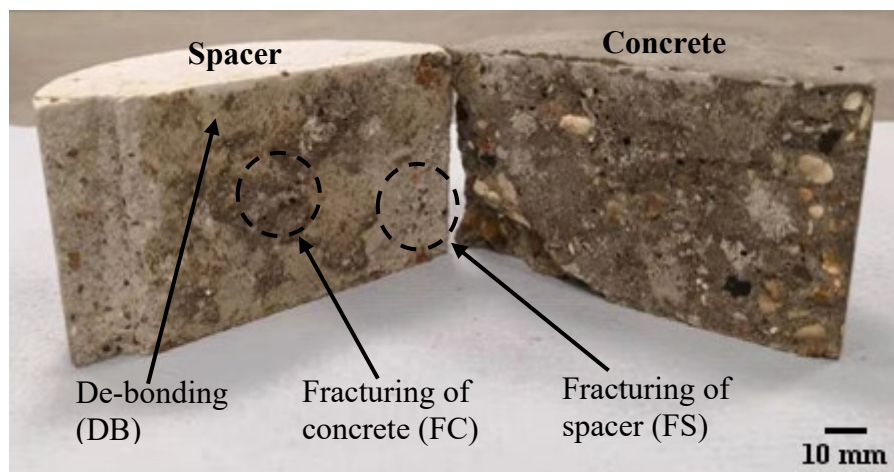


Figure 7.5 Fractured surface of the spacer-concrete interface showing example failure modes (F-S60(0.35) cured for 14d)

Table 7.6 Typical failure modes. DB = de-bonding, FS = fracturing of spacer, FC = fracturing of concrete

Sample ID	Curing time (d)	Typical failure mode
F-S0(0.4)	7; 14; 28; 91	DB
F-S80(0.4)	7; 14; 28; 91	DB
F-S0(0.35)	7; 14; 28; 91	DB
F-S60(0.35)	7	DB
	14	DB & FS & FC
	28; 91	FS & FC
F-S80(0.35)	7; 14	DB & FS
	28	FS & FC
	91	FS
Sp-S0(0.4)	7; 14; 28; 91	FS & FC
Sp-S80(0.4)	7; 14; 28; 91	FS & FC
Sp-S0(0.35)	7; 14; 28; 91	FS & FC
Sp-S60(0.35)	7; 14; 28; 91	FS & FC
Sp-S80(0.35)	7; 14; 28; 91	FS & FC

As mentioned earlier, the failure mode of samples with flat spacers was mainly de-bonding of the interface. However, at low w/b ratio, the incorporation of slag and increase in curing time appear to shift the failure mode from DB-dominant to gradually more fracturing (FS or FC). In addition, the higher the slag replacement ratio, the earlier the failure mode transformation occurred. This again indicates that the addition of slag promotes spacer-to-concrete chemical bonding, as evidenced from the appearance of fracturing. The intensity of chemical bonding is expected to be related to the quantity of unreacted cement or slag particles on the spacer surface. Therefore, spacers with 80% slag content showed earlier fracturing compared to spacers with 0 or 60% slag. This also coincides with the higher bond strength for samples containing flat spacers with 80% slag and those containing flat spacers with 0 and 60% slag (Figure 7.3). It should also be noted that samples with 80% slag replacement failed mainly through FS after curing for 91d. This may be attributed to the lower strength of spacers compared to concrete, but it is also an indication of good spacer-to-concrete bonding. However, at w/b ratio of 0.4, no fracturing failure was observed on samples with flat spacers, even when using 80% slag. This could be due to the lower quantity of unreacted cementitious particles on the spacer surface resulting from the more sufficient hydration at higher w/b ratio.

7.3.3 Mass transport properties of reactive spacer-concrete composites

Mass transport properties of composite samples with slag-based spacers are shown in Figure 7.6. It can be seen that all mass transport properties decreased with increase of curing time, regardless of the type and composition of the spacers. Water sorptivity showed the most significant drop between the short-term ($< 28\text{d}$) and long-term (365d) values. The data is consistent with the expectation of densification and refinement of the pore structure particularly the capillary pores with prolonged curing time.

Compared to the 28d results of concrete samples with the same w/c ratio of 0.4 and embedded commercial cementitious spacers (shown in Table 5.2), most composite samples with slag-based spacers showed lower mass transport, particularly diffusivity and water sorptivity. This indicates clear improvements in terms of transport resistance, which could be attributed to the improved spacer, and more likely to the enhanced spacer-concrete interface. This is consistent with the comparison presented in Chapter 7.3.1 showing that the 28d sorptivity of the slag-based spacer generally lie within the range of values from commercial spacers. Therefore, the reduction in transport properties is attributed to improved spacer-concrete interface rather than the spacer itself.

Comparing the samples with same type of spacers (split or flat) and equal slag content, mass transport properties decreased with the decrease in w/b ratio. This again is consistent with results shown in Chapter 7.3.1, where spacers with lower w/b ratios have smaller mass transport at 7d and 28d. In addition, mixes with lower w/b ratio will maintain a higher content of unreacted cementitious particles on the surfaces of spacers. Therefore, the combined benefits (i.e. reduced porosity and increased unreacted cementitious materials) is reflected in the reduction of mass transport properties of the spacer-concrete composites.

At equal w/b ratio, using higher slag replacement generally led to a lower mass transport regardless of the type of spacers (flat or split). An interesting observation was made of the results from samples with spacers containing 60% and 80% slag at w/b ratio of 0.35. Spacers with 60% slag were found to be optimal in decreasing mass transport at 7d and 28d, and a small increase was observed when the slag content was increased to 80%. However at 365d, the diffusivity and permeability of composite samples with spacers made of 80% slag were lower than the values for samples with 60% slag-based spacers. The difference was more pronounced with flat spacers. This provides another evidence of an improved spacer-concrete interface microstructure at higher slag content and its effectiveness, especially at low w/b ratio.

The performance of composite samples was improved when using split spacers compared to flat spacers. To evaluate this further, the percentage decrease of each property benchmarked against the respective sample with flat spacers of the same composition was calculated and shown in Figure 7.7. The highest percentage improvement was observed for permeability, especially at longer curing time. This is suspected to be related to the improved cracking resistance at the split spacer-concrete interface during conditioning at 50°C, and is consistent with the fact that permeability is highly sensitive to presence of cracks (Wu et al., 2015). The percentage decrease in diffusivity and sorptivity ranged from 2% to 44% and 16% to 55% respectively, showing no obvious correlation with composition or curing time.

A number of factors could lead to the improved performance of split spacers over flat spacers. For example, the splitting method would expose more unreacted cementitious particles with larger specific surface areas on the spacers, and therefore bring additional benefits in refining the microstructure around the spacer-concrete interface through chemical reaction when cast against concrete. Additionally, shrinkage of the freshly-cast concrete and differential thermal movement between spacer and concrete during the conditioning at the elevated temperature could induce microcracking around the spacer-concrete interface. The generation of surface roughness would be beneficial for improving the crack resistance as well as preventing the propagation of continuous cracks. However, it is difficult to isolate and quantify the impact of each factor separately with different spacer compositions and curing ages.

Figure 7.8 shows the mass transport properties of spacer-concrete composite samples normalised to the value of the control sample F-S0(0.4) (same to the control sample F-M in Chapter 6) at the respective age. Compared to the control sample (F-S0(0.4)), composites with split spacers containing slag showed decreased mass transport properties by a factor of 0.4 to 0.6 for diffusivity, 0.1 to 0.6 for permeability and 0.3 to 0.7 for sorptivity. The corresponding values for samples with flat spacers containing slag were 0.4 to 0.8 for diffusivity, 0.2 to 0.8 for permeability, and 0.5 to 0.9 for sorptivity respectively. For samples with same spacer type and composition, the reduction factor of mass transport properties (particularly diffusivity and sorptivity) showed mild changes with the curing time of the composite sample. These indicate the effectiveness of using slag-based spacers at both early and later ages. However, the effectiveness should also be assessed from another perspective since the reduced mass transport is a combined effect of the improvements occurring in the spacer part and the spacer-concrete interface. Previous research (Alzyoud et al., 2016) on concrete containing conventional cementitious spacers found a highly porous spacer-concrete interface of around 50 µm wide. It

is very difficult to isolate the spacer-concrete interface of such size and evaluate its mass transport properties independently. Therefore other techniques were used to investigate the spacer-concrete interface and these are presented in the following chapters.

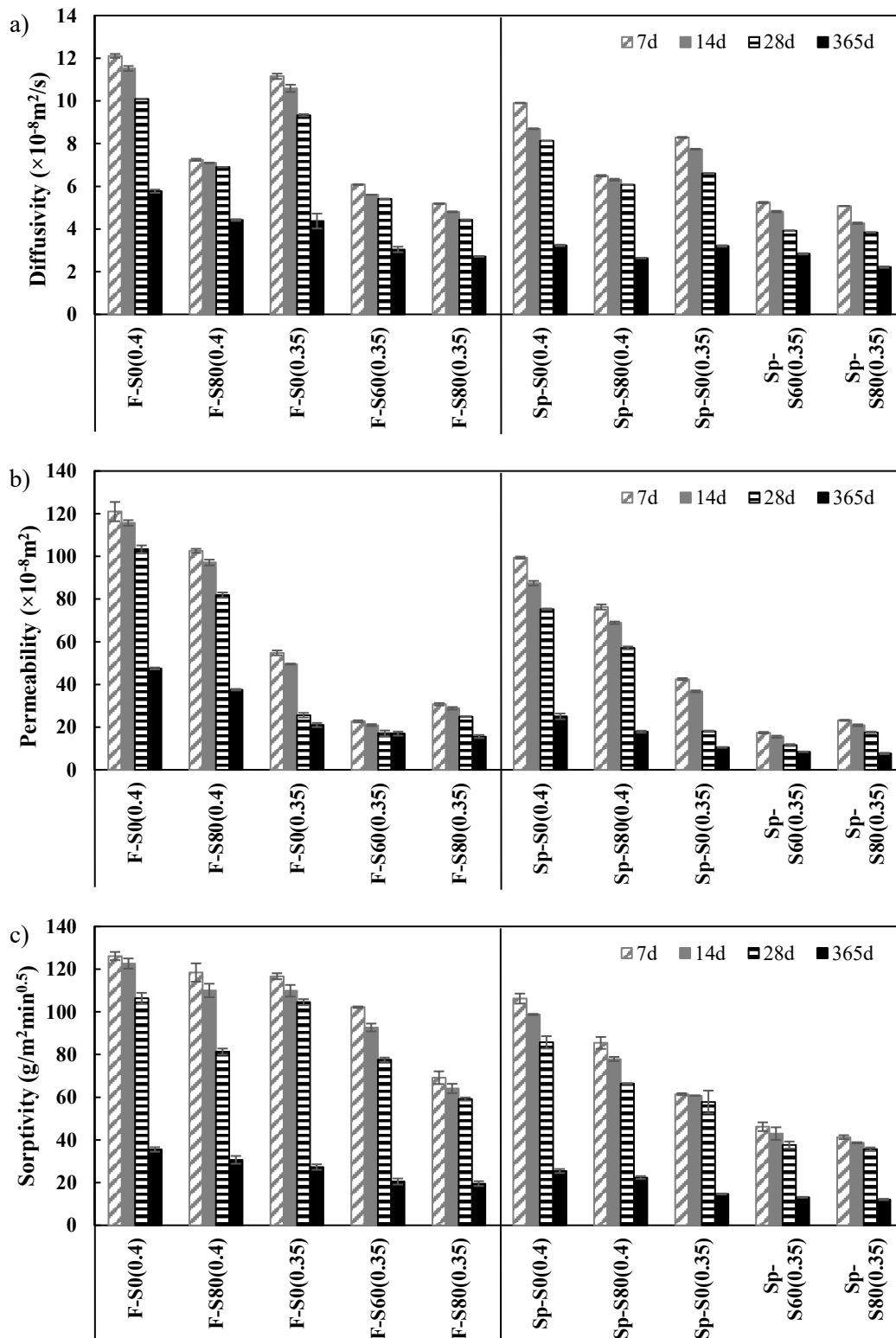


Figure 7.6 Mass transport properties of composite samples with slag-based spacers: a) oxygen diffusivity; b) oxygen permeability; c) water sorptivity

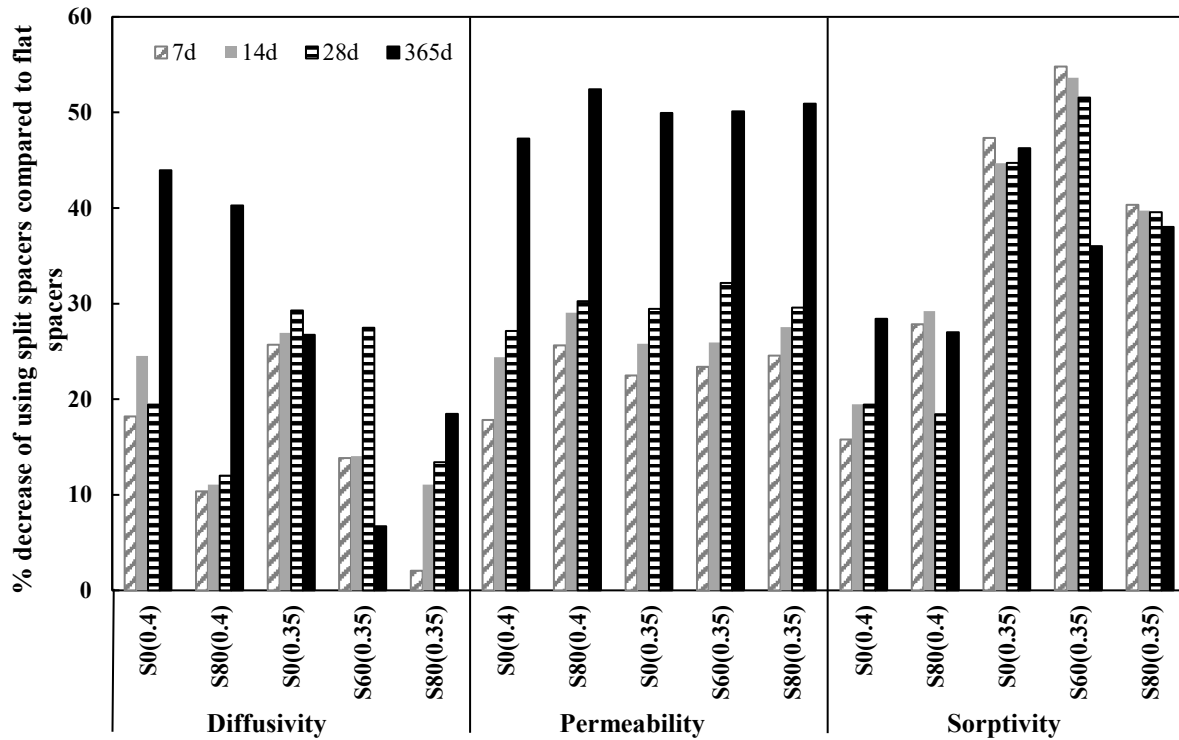


Figure 7.7 Percentage decrease on mass transport properties induced by using split spacers compared to composite samples with flat spacers of the same composition

Figure 7.9 compares the normalised mass transport properties of the composite samples with split spacers containing slag or fibres. Compared to the control sample (F-S0(0.4)), composite samples with split spacers containing slag are more effective in decreasing diffusivity and sorptivity than most split spacers with fibre reinforcement at the same w/b ratio. The exception occurs to the composites with split spacers containing polypropylene fibre (PPF), which showed lower normalised diffusivity and sorptivity at 365d. The normalised values were even lower than those of the composite samples with split reactive spacers at a lower w/b ratio (Sp-S60(0.35) and Sp-S80(0.35)). This is attributed to the more significant pore refining effects (such as decreasing the size and number of capillary pores (Zhang & Li, 2013; Bagherzadeh, Sadeghi & Latifi, 2012; Zhang et al., 2018)) of PPF than slag that occurred both in the spacer and at the spacer-concrete interface. Differently, composites with split spacers containing slag were constantly less effective in decreasing permeability than all composites with fibre-reinforced split spacers at same w/b ratio, irrespective of the curing time. It is attributed to the milder microcracking in the fibre-reinforced split spacers and at their interface with concrete because the fibre bridging effect could reduce the microcrack size and inhibit microcrack propagation.

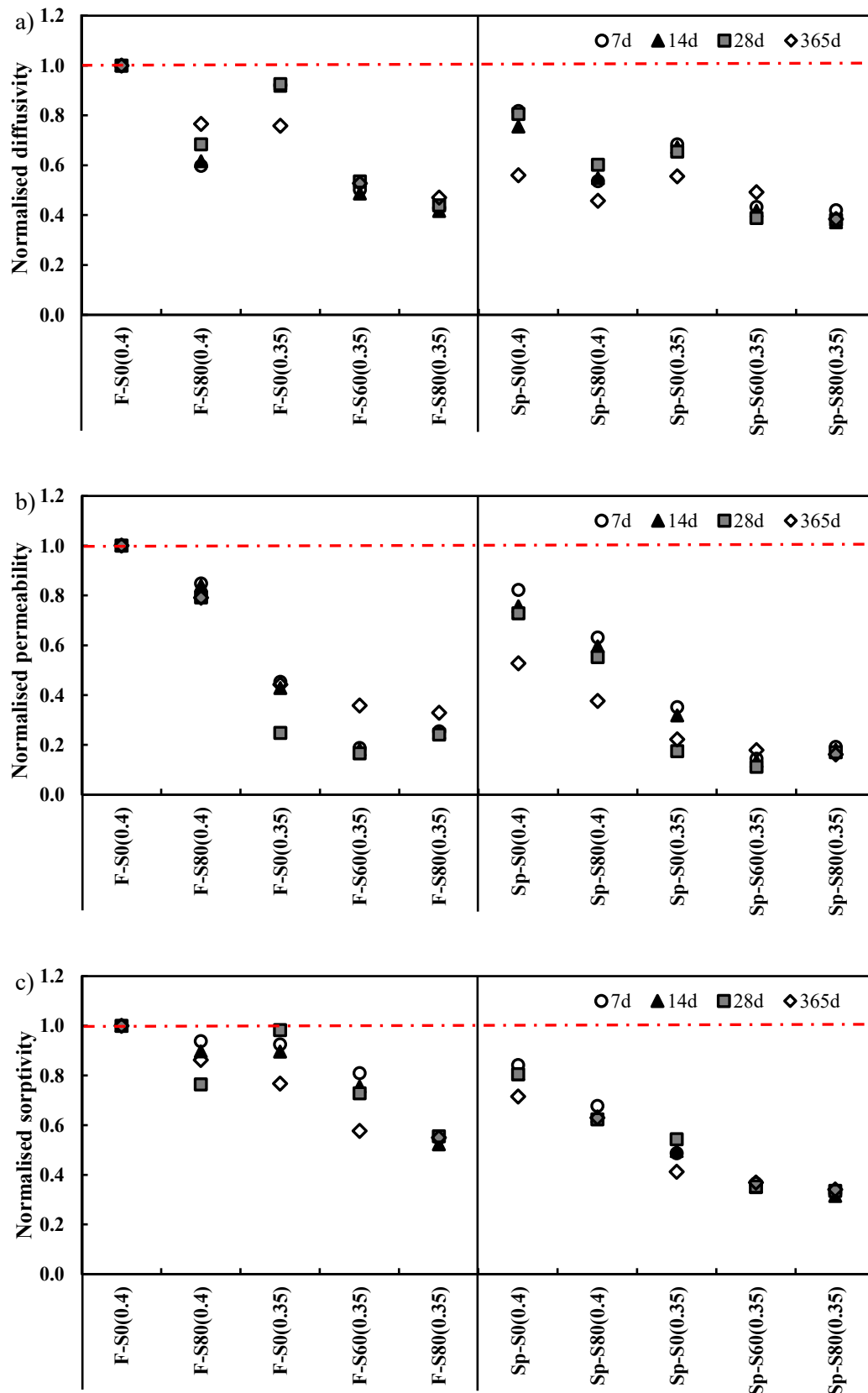


Figure 7.8 Normalised mass transport properties of slag-based spacer-concrete composites: a) diffusivity; b) permeability; c) sorptivity. The data is normalised to the respective values from the control composite sample (F-S0(0.4)) at same age

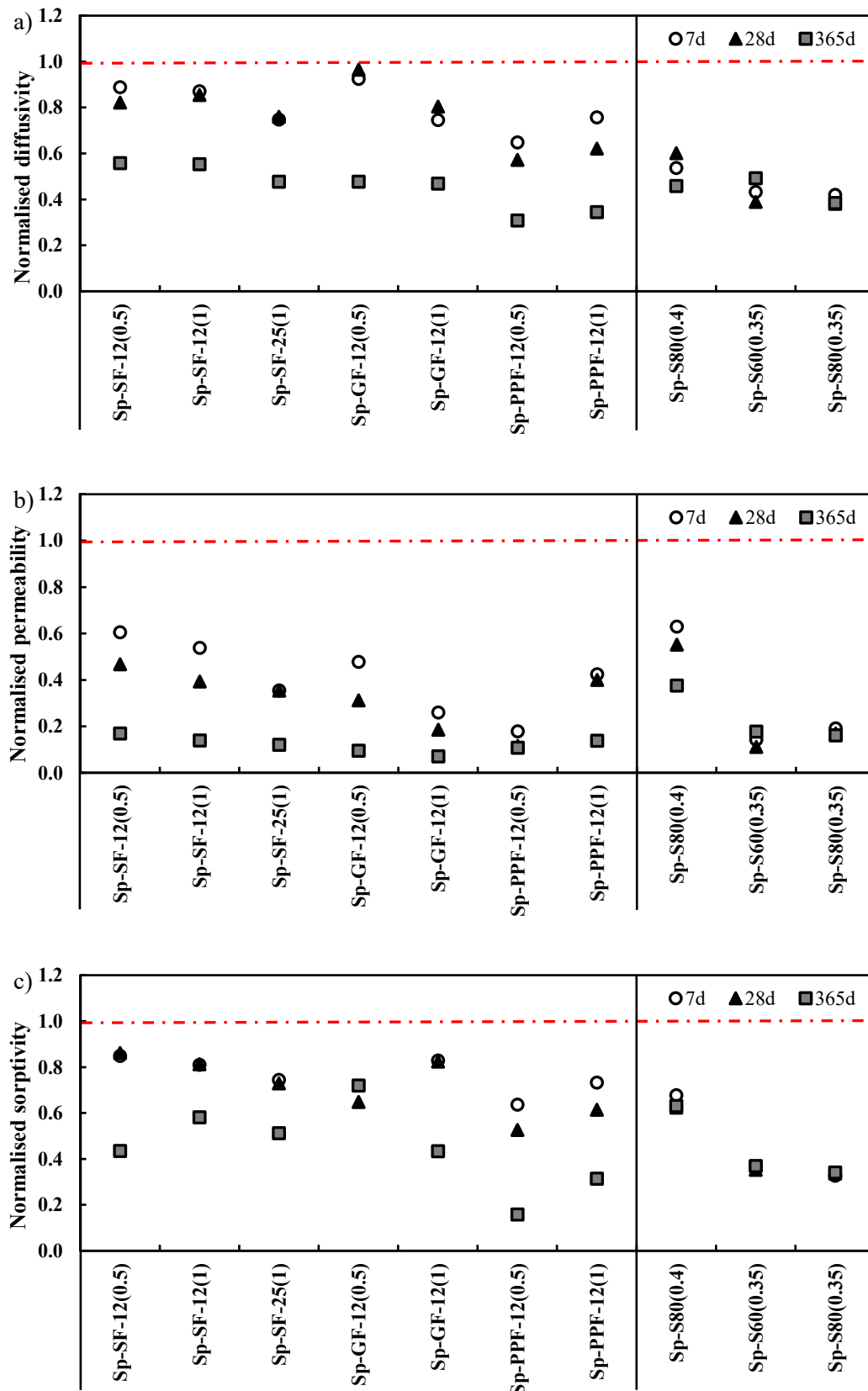


Figure 7.9 Normalised mass transport properties of composite samples containing split spacers with fibre reinforcement and reactive surfaces: a) diffusivity; b) permeability; c) sorptivity. The data is normalised to the respective values from the control composite sample (F-S0(0.4)) at same age

7.3.4 Fluorescent epoxy impregnation

Pressure impregnation of fluorescence epoxy was conducted to enhance the understanding of the microstructure and transport properties at the spacer-concrete interface. Figure 7.10 and Figure 7.11 show cross sections of 7d and 28d spacer-concrete composites after epoxy impregnation from the bottom edge. The concrete and the spacer are allocated on the left and right hand side of the images respectively. Unfortunately, the image for sample containing F-S0(0.4) cured for 7d is not available due to the debonding at spacer-concrete interface occurred when conditioning the sample. This is suspected to be caused by the harsh drying condition at 50°C and weak bonding between the spacer and concrete.

The data show substantial epoxy penetration through the spacer-concrete interface, particularly for samples containing flat spacers. A small amount of epoxy intrusion occurred on the bottom side of the concrete and spacer, but mostly around the interfacial transition zone between cement paste and aggregate particles. In some samples, such as F-S0(0.35) cured for 7d, penetration was also observed from the spacer-concrete interface into the concrete side, primarily along the edges of the aggregates. These are attributed to the aggregate-cement paste interfacial transition zone which is known to be more porous and microcracked compared to the bulk paste region.

There were no noticeable cracks or preferential impregnation through the spacer itself, which is a positive sign and gives confidence that the splitting process during the spacer production did not induce damages to the spacer. To quantify the extent of the epoxy penetration, impregnation depth (D_{IT}) at spacer-concrete interface was measured and normalized to the sample thickness (T). The results are shown in Table 7.7.

At 7d, the epoxy penetrated across the entire cross-section of most samples with flat spacers. Only the sample with flat spacer containing 80% slag at low w/b ratio showed incomplete penetration, but still substantial (more than half of the specimen thickness). Epoxy penetration was clearly reduced when using split spacers and with the increase in slag content, in particular at w/b ratio of 0.35 and prolonged curing.

After 28d, only samples with F-S80(0.4) spacer had epoxy penetration through the entire thickness while other samples with flat spacers had penetration depths greater than half of the specimen thickness. The penetration depth of F-S80(0.35) sample decreased obviously after

28d curing. Samples with split spacers containing 60% and 80% slag showed the smallest epoxy penetration through the spacer-concrete interface at 28d.

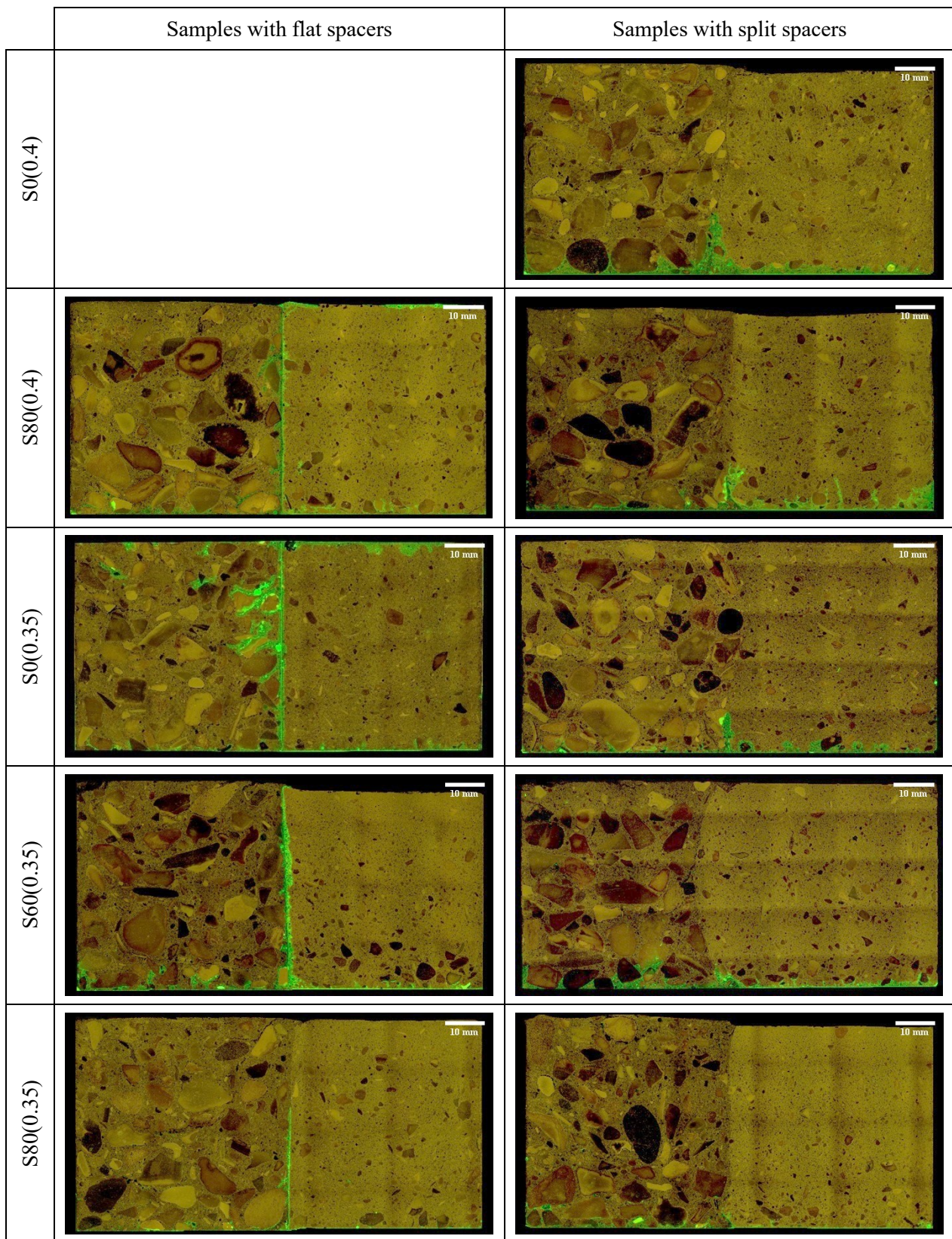


Figure 7.10 Fluorescent epoxy impregnation of samples with slag-based spacers (7d curing)

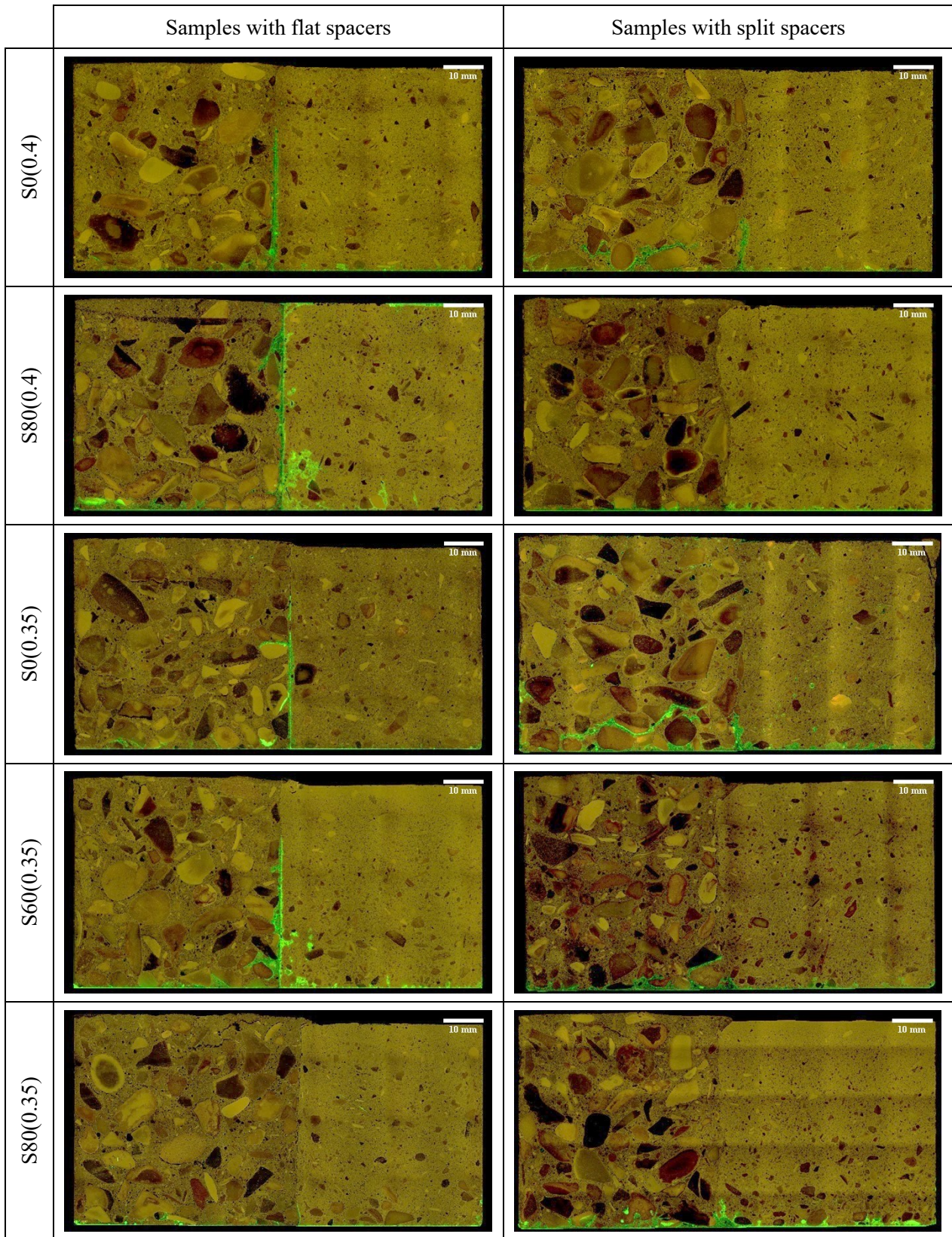


Figure 7.11 Fluorescent epoxy impregnation of samples with slag-based spacers (28d curing)

Table 7.7 Ratio of impregnation depth at spacer-concrete interface to sample thickness (%)

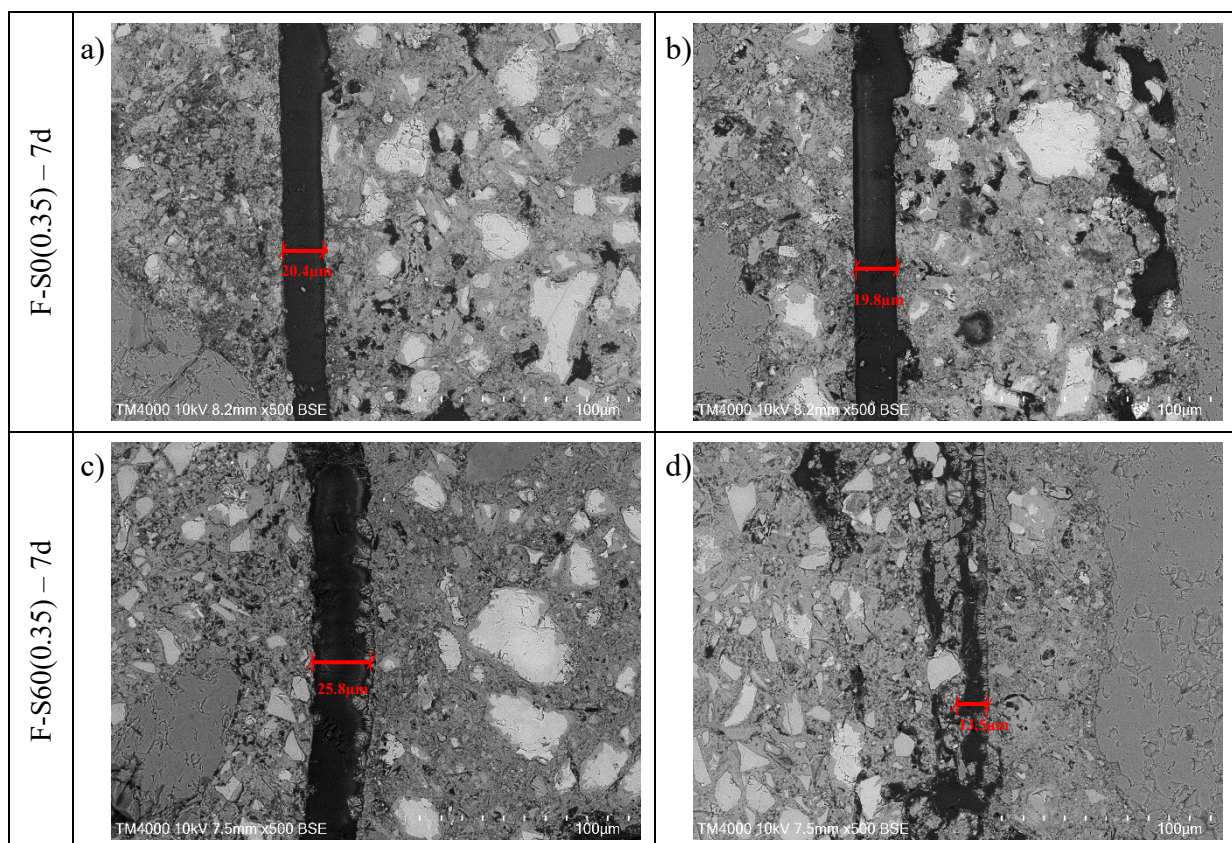
Curing time (d) Sample ID	7	28
F-S0(0.4)	-	73.8
F-S80(0.4)	100.0	100.0
F-S0(0.35)	100.0	75.7
F-S60(0.35)	100.0	80.8
F-S80(0.35)	59.8	11.5
Sp-S0(0.4)	30.8	25.3
Sp-S80(0.4)	24.1	6.9
Sp-S0(0.35)	20.2	19.2
Sp-S60(0.35)	12.7	8.6
Sp-S80(0.35)	11.5	7.6

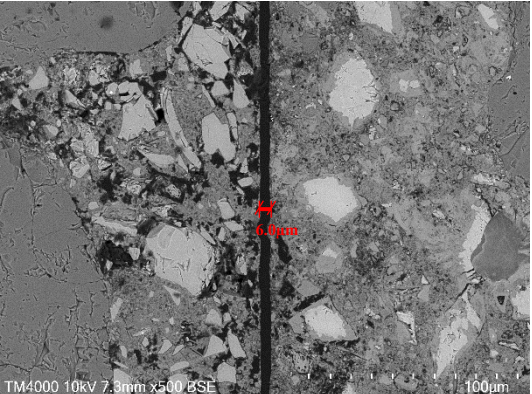
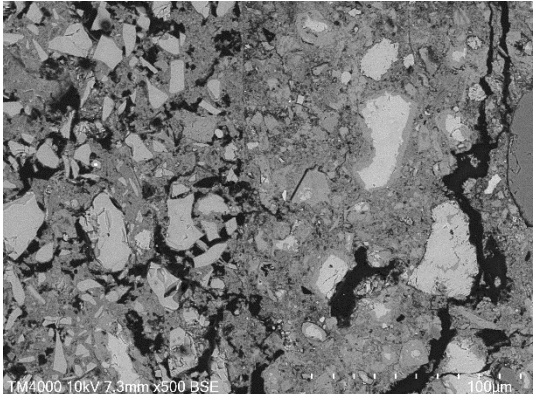
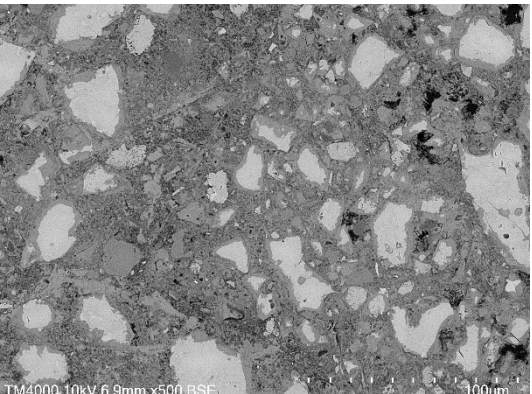
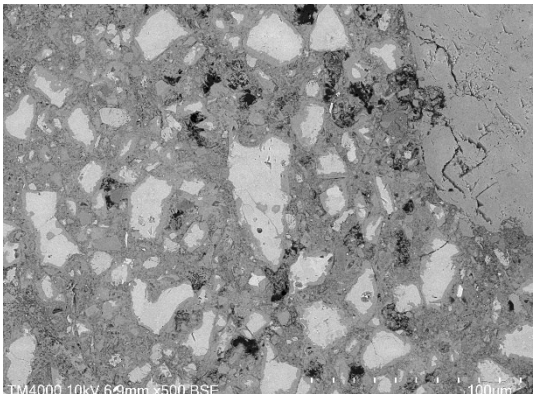
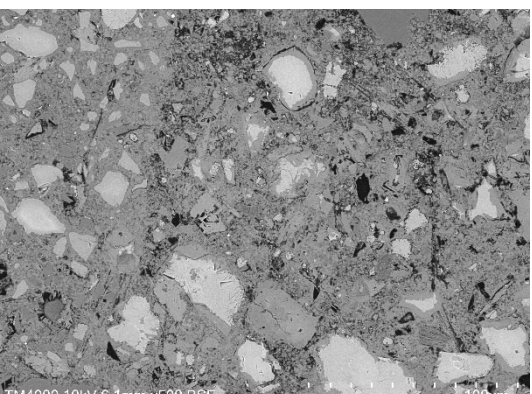
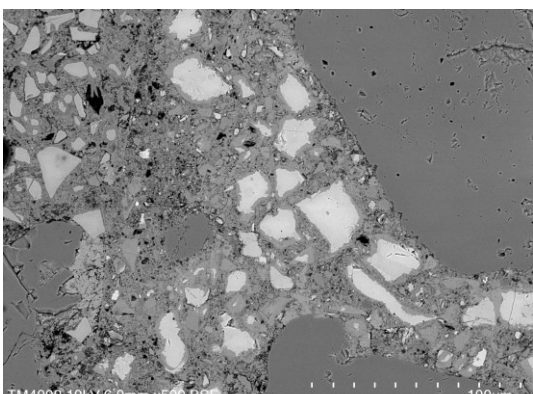
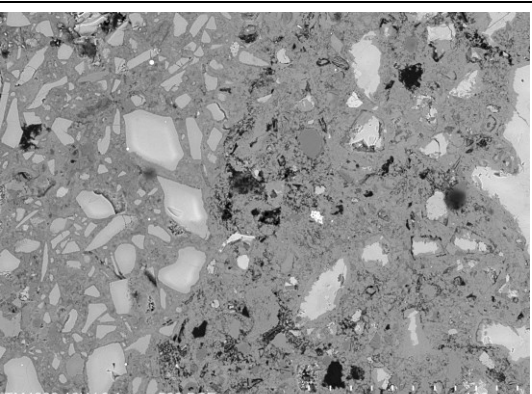
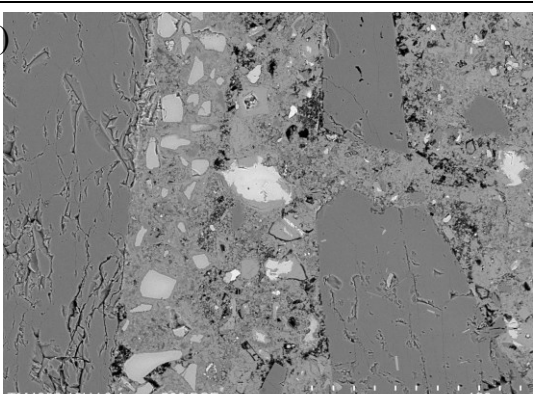
7.3.5 Microstructure of reactive spacer-concrete interface

Figure 7.12 shows example BSE images (two for each sample) of the spacer-concrete interface microstructure. The spacer and concrete parts are shown on the left and right hand side of the images respectively. Samples with flat spacers clearly show a debonding crack at the spacer-concrete interface and this is consistent with the low bond strength results from Chapter 7.3.2. Therefore the bonding developed after 7d curing is not sufficient to withstand the stress induced by shrinkage or thermal movements during sample conditioning. However, the debonding crack seemed to be inhibited to some extent in the mixes containing slag. At 0% slag, the debonding crack width was generally around 20 μm propagating through the entire interface. At 60% slag, the debonding crack width was spatially variable, and ranged from 14 to 26 μm . Some reaction products can be observed forming along the edges of the crack or the spacer-concrete interface. This is in contrast to the clear cracking surfaces found on sample without slag. At 80% slag, the width of the de-bonding crack decreased to about 6 μm and some locations were able to maintain a bond between the concrete and the spacer (Figure 7.12d). These observations are consistent with the bond strength results and failure mode observed in Chapter 7.3.2.

Composite samples containing split spacers displayed a very different interfacial microstructure characteristics that are much denser and free of debonding cracks. Two images

from each sample were shown in Figure 7.12, highlighting interfaces with (shown in the first image, such as Figure 7.12h for 7d sample Sp-S0(0.35)) and without (shown in the second image, such as Figure 7.12i for the same sample) closely packed aggregates. No obvious defects such as microcracks were observed even when there are aggregates nestled near the spacer-concrete interface. In general, the spacer-concrete interface region showed very few unreacted cementitious particles left, especially at 365d. This suggests that further cement hydration, slag hydration or pozzolanic reaction have occurred around this region, and thus explains the dense microstructure and improved bonding between these spacers and concrete. This has occurred to the extent that it became challenging to identify the exact location of the spacer-concrete interface. As such, it is also challenging to quantify the amount of unreacted particles and relate these to the location of the spacer-concrete interface.



F-S80(0.35) – 7d	e) 	f) 
Sp-S0(0.35) – 7d	h) 	i) 
Sp-S60(0.35) – 7d	j) 	k) 
Sp-S80(0.35) – 7d	l) 	m) 

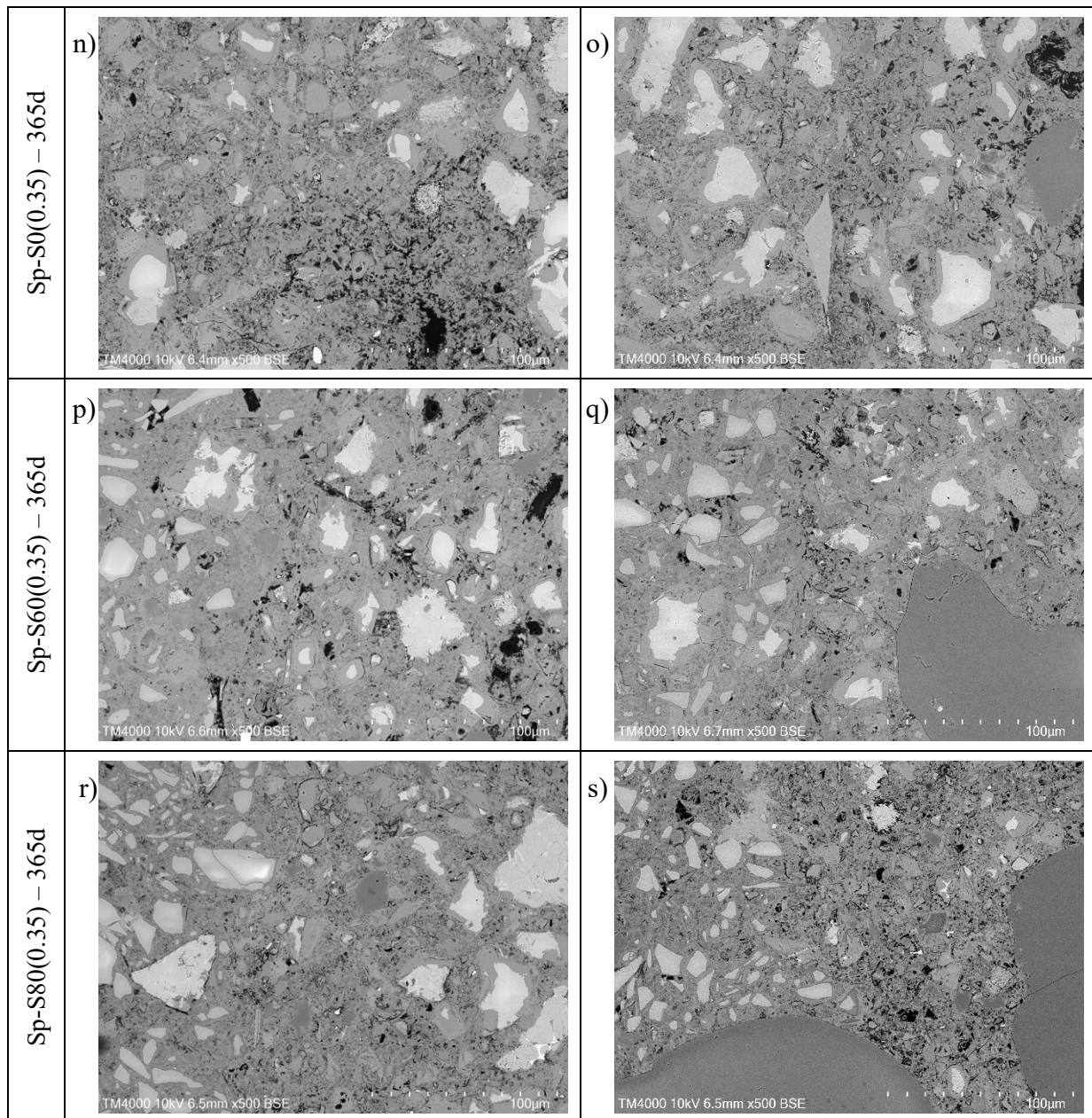


Figure 7.12 BSE images showing typical spacer-concrete interface microstructure of composite samples with flat and split reactive spacers

7.3.6 Accelerated carbonation

Carbonation resistance of the spacer-concrete composite samples was determined with phenolphthalein spray test after exposing the top and bottom sides of the composite samples to 3% CO₂, 75% RH and 20°C for 224d. The samples were cured in a fog room (100% RH, 20°C) for 28d and conditioned in a conditioning chamber (75% RH, 20°C) containing soda lime until

constant weight before they were exposed to the CO₂. It was observed that carbonation was most extensive in the spacer part or at the spacer-concrete interface, while very little carbonation was found in the concrete part for all samples. The average carbonation depths from the top and bottom sides of the spacer are listed in Table 7.8.

No obvious correlation was found between carbonation depth and the type of spacer (flat or split). The carbonation depth on the spacer was more likely to be dependent on their composition, which increased with higher w/b ratio and with the increase in slag content. Addition of slag decreased the carbonation resistance of the spacer significantly, especially at 80%. This agrees with the general findings from previous research (Gruyaert et al., 2013; Ceukelaire & Nieuwenburg, 1993; Sisomphon & Franke, 2007) and is attributed to the lower alkalinity and portlandite content in the slag-blended systems. Another observation is that deeper carbonation occurred at the top compared to the bottom side, and the difference became more apparent with higher slag replacements. This could be due to bleeding effects, which is exacerbated by the presence of slag because of the delay in setting and hydration.

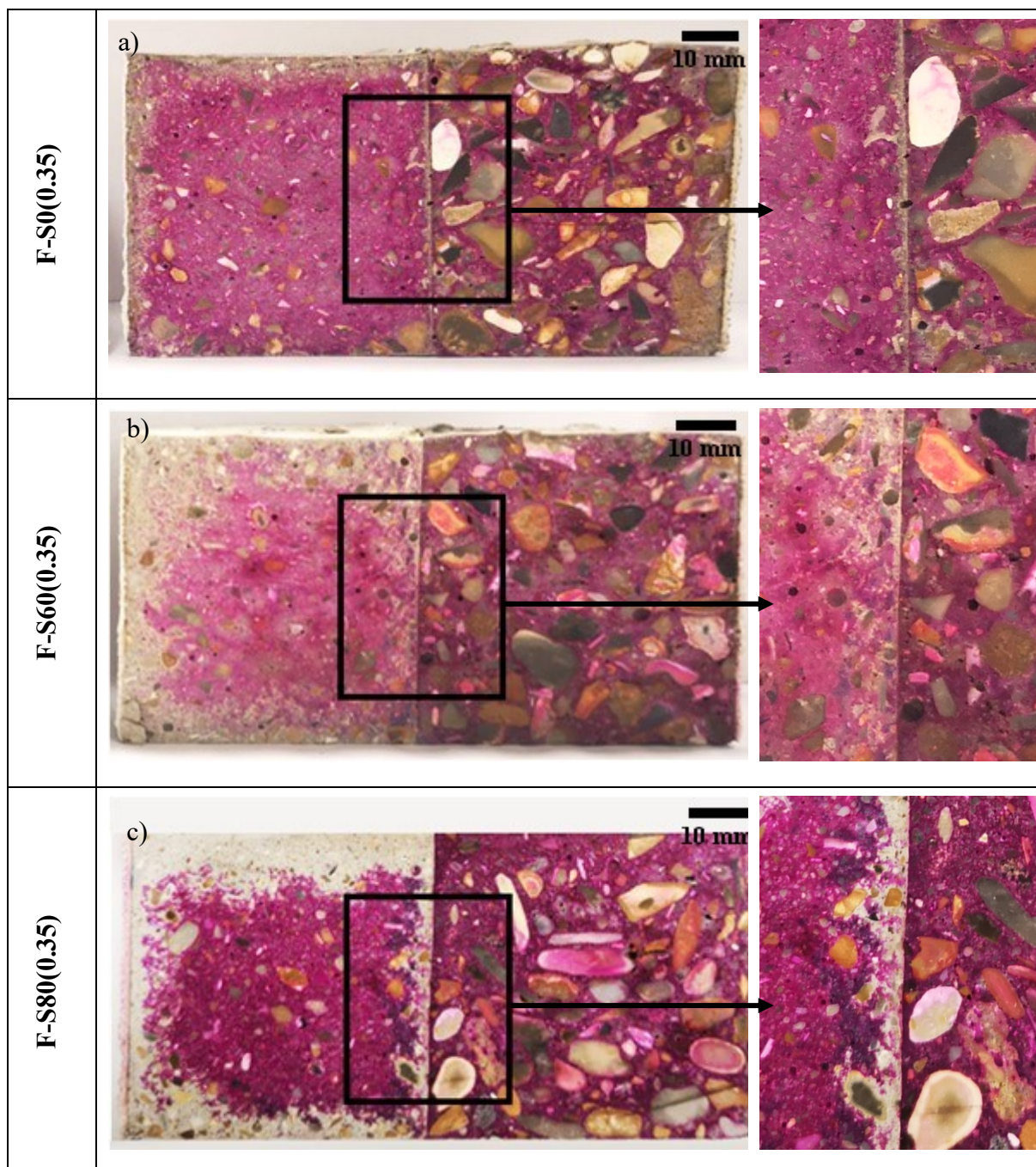
Table 7.8 Carbonation depth in spacers and carbonation width at spacer-concrete interface of samples with slag-based spacers

Spacer type	Flat spacer			Split spacer		
	Depth in spacer		Width at the interface	Depth in spacer		Width at the interface
	Top	Bottom		Top	Bottom	
S0(0.4)	1.78 (0.19)	0.92 (0.19)	1.02 (0.05)	2.34 (0.21)	1.34 (0.4)	-
S80(0.4)	11.88 (0.92)	9.18 (1.38)	3.62 (0.12)	11.44 (1.13)	6.9 (0.57)	-
S0(0.35)	1.46 (0.21)	0.96 (0.11)	1.00 (0.09)	1.08 (0.08)	0.92 (0.08)	-
S60(0.35)	2.58 (0.61)	0.98 (0.99)	0.25 (0.04)	2.98 (0.29)	0.8 (0.74)	-
S80(0.35)	10.46 (0.4)	7.62 (0.51)	1.23 (0.34)	9.45 (3.23)	6.71 (1.44)	-

Note: Unit is mm; Each result based on five measurements; Standard deviation is marked in the bracket; “-” represents no obvious carbonation observed.

The interface between flat spacers and concrete were generally entirely carbonated (Figure 7.13a and c). One exception was found in the samples containing flat spacer with 60% slag and w/b ratio of 0.35, where the spacer-concrete interface was partially carbonated from the top surface with a depth of 20 mm (Figure 7.13b). The average width of the carbonation region at spacer-concrete interface was also measured and presented in Table 7.8. Again, spacers with

60% slag and w/b ratio of 0.35 was optimal in terms of its carbonation resistance. This is in contrast to the results of previous chapters, where 80% slag was found to be more beneficial in generating a better bond between the flat spacer and concrete. However, carbonation resistance is unique in the sense that it is dependent on the alkalinity of the system in addition to pore structure. The greater extent of carbonation in spacers containing 80% slag could lead to high carbonation shrinkage and stress concentrations at the spacer-concrete interface, which could cause further changes to the microstructure (e.g. cracking) and accelerate CO₂ penetration.



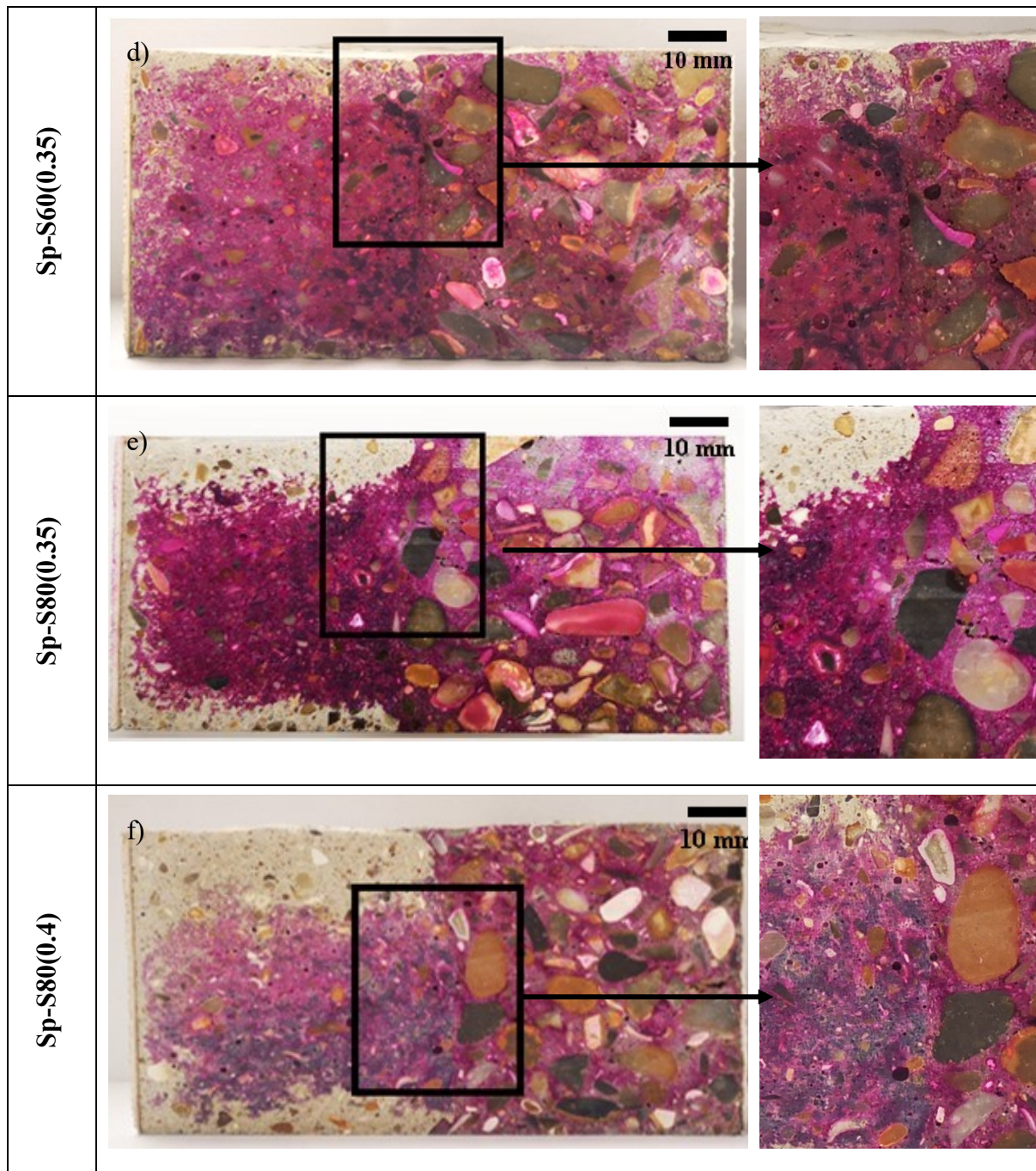


Figure 7.13 Cross-section images shown the extent of carbonation on the spacer, concrete and spacer-concrete interface. The interfaces with flat spacers showed extensive carbonation (a, b, c) while interfaces with split spacers containing slag showed no carbonation (d, e, f).

It is interesting to note that samples containing split spacers experienced no detectable carbonation at the spacer-concrete interface (Figure 7.13d, e and f). In general, compared to the control sample F-S0(0.4), which was fully carbonated through the spacer-concrete interface, samples with split spacers showed great capacity for slowing the progress of carbonation. The resistance to carbonation at the interface was high even for split spacers containing high

amounts of slag. This shows that the dense interface microstructure (Figure 7.12) produced from the additional chemical bonding between split spacers and concrete have led to an improved resistance against carbonation, relative to the case of flat spacers. In such systems, it is worth noting that the spacer therefore become the critical component for determining the carbonation resistance of the concrete cover rather than the spacer-concrete interface.

7.4 Conclusions

This chapter presents an investigation on improving the spacer-concrete interface through developing spacers with reactive surface. Mortars containing three slag contents (0, 60% and 80%) and two w/b ratios (0.35 and 0.4) were used to produce spacers with flat surfaces and rough surfaces (through the proposed splitting method). Performance of these spacers and their effects on concrete were tested at different curing ages. The developed split spacers containing slag were found to be effective in enhancing the bond strength, mass transport resistance, epoxy impregnation resistance under high pressure, carbonation resistance and microstructure at the spacer-concrete interface. Split spacers containing higher slag contents at lower w/b ratio showed higher effectiveness. Flat spacers were only effective when containing high slag content at low w/b ratio, but their effectiveness was consistently lower than that of split spacers due to lower unreacted particle contents on the surface and the sensitivity to cracking and debonding at the spacer-concrete interface. The developed split reactive spacers showed higher effectiveness in reducing the diffusivity and sorptivity of spacer-concrete composites than most fibre-reinforced split spacers of equal w/b ratio developed in Chapter 6, but lower effectiveness in improving the bond strength and permeability resistance, particularly at 7d.

Chapter 8 Conclusions and recommendations

8.1 Thesis summary including main conclusions

The inclusion of spacers in concrete structures has been found to be detrimental to mass transport properties relevant to long-term durability, particularly through the generation of a porous spacer-concrete interface. However, previous research (Alzyoud et al., 2016) was limited to the use of one type of cementitious spacer. An extensive survey carried out in this thesis found a huge diversity in cementitious spacers that are commercially available, but with limited information provided on their properties. Furthermore, the performance of various cementitious spacers used in the industry and their effects on the durability of concrete structures are not well appreciated. There is also a lack of research on improving the spacer-concrete interface. Therefore, the aim of this research is to understand the performance of cementitious spacers and their effects on concrete durability, and to develop new improved cementitious spacers that could provide better chemical and mechanical bonding with concrete, and thereby improving the long-term durability of concrete structures. This aim was achieved through fulfilling the five objectives as discussed in Chapter 1.2.

Firstly, nine types of cementitious spacers (categorised into S spacers and M spacers according to their function) from five leading manufacturers from the UK and Germany were shortlisted for detailed characterisation. Their physical properties (e.g. cover depth, thickness, cross-sectional area, volume and density), mechanical properties (compressive strength, modulus of rupture and dynamic Young's modulus), durability (e.g. water sorptivity, porosity, carbonation in the as-received condition and carbonation resistance) and microstructural properties were investigated. Results showed that cover depths and compressive strength of major spacers were below the tolerance as defined by the British Standard (BS 7973-1:2001, 2001). Some spacers were already carbonated in the as-received condition, which indicates their low carbonation resistance, and potentially improper processing and storage condition. Large variations in properties were observed between different spacer types, particularly durability related properties such as water absorption, porosity and carbonation resistance. This was attributed to a number of factors, such as variations in mix compositions and processing conditions. This clearly underscored the lack of industry regulation, guidance and appreciation on the importance of spacers.

The collected cementitious spacers were then embedded in concrete at two w/c ratios (0.4 and 0.6) to determine their effects on concrete microstructure and mass transport properties (oxygen diffusivity, oxygen permeability, water sorptivity and epoxy impregnation). The incorporation of these spacers was found to increase mass transport properties (by a factor of 1.2 to 2.6 for diffusivity, 1.2 to 30.8 for permeability and 1.1 to 2.8 for sorptivity) in all cases. A more pronounced increase was observed when the spacers were embedded in concrete with a low w/c ratio. Permeability was the most negatively affected transport property with highest variation between samples. These effects could be attributed to both the properties of the spacer itself and the generation of a porous spacer-concrete interface. For example, the permeability of the spacer-concrete composite samples showed correlations with the porosity of the embedded spacers. A correlation between water sorptivity of the composite samples and the sorptivity of the embedded spacer was also observed for concretes with low w/c ratio. Epoxy impregnation was most substantial at the spacer-concrete interface compared to that occurring within the spacer and the bulk concrete, regardless of the spacer type and w/c ratio of the concrete. Half of the composite samples showed complete impregnation through the spacer-concrete interface.

These results showed clear detrimental effects of the spacer-concrete interface on concrete durability. To improve the spacer-concrete interface, an innovative method for producing spacers with rough surfaces, exposed fibres and unreacted cementitious particles was developed, which corresponds to the second objective proposed in Chapter 1.2. This was achieved through splitting the spacer with pre-fabricated grooves at designated positions that was proven to be effective without generating additional damages to the spacer. The method was then applied to develop novel cementitious spacers with exposed fibres and reactive surfaces which could enhance their mechanical and chemical bonding with concrete.

To achieve the third objective of investigating the potential of fibre reinforced cementitious composites, three types of fibre (steel, glass and polypropylene) with two lengths (12 and 25 mm) were used at two volume fractions (0.5% and 1%) to prepare spacers with fibre-reinforcement. Two w/c ratios (0.3 and 0.4) were adopted for preparing the spacers. Compared to flat spacers of the same composition (corresponding to the fifth objective), the developed split spacers with exposed fibres were found to be effective in increasing bond strength (by a factor of 1.4 to 1.9), ductility and resistance to cracking at spacer-concrete interface when subjected to tensile stress. The level of improvement is dependent on the fibre type, length, dosage and the number of fibres exposed on the surface. Split spacer with 25 mm steel fibre at

1% vol. showed the highest bond strength and cracking resistance after 28 d curing (100% RH, 21°C). Compared to conventional non fibre-reinforced flat spacers, split spacers with exposed fibres were also found to be effective in decreasing mass transport properties (by a factor of 0.3 to 0.9 for diffusivity, 0.1 to 0.6 for permeability and 0.2 to 0.9 for sorptivity) and epoxy impregnation through the spacer-concrete interface. At the optimal dosage, polypropylene fibre was the most effective whilst 12 mm steel fibre was the least effective, regardless of curing time. In addition, fibre-reinforced split spacers showed a denser spacer-concrete interface microstructure than those obtained with conventional commercial cementitious spacers.

Furthermore, ground granulated blast furnace slag (referred to as slag) was used as an alternative binder for producing spacers with reactive surfaces that would undergo chemical reactions with freshly cast concrete (corresponding to objective 4). Main variables for producing the novel spacers include slag replacement content (0, 60%, 70% and 80% wt.), water/binder (w/b) ratio (0.35 and 0.4) and spacer type (split, produced by the new developed method and flat, as-cast). Compared to the conventional flat spacers (also corresponding to objective 5), split spacers with exposed unreacted cementitious particles were more effective in enhancing the bond strength (by a factor of 1.4 to 2.2), transport resistance (decreasing the diffusivity, permeability and sorptivity by a factor of 0.4 to 0.6, 0.1 to 0.6 and 0.3 to 0.7 respectively) and cracking and de-bonding resistance at spacer-concrete interface. More substantial improvement was found when using split spacers with high slag content and low w/b ratio. Despite the spacer composition, split spacer-concrete interface consistently showed lower epoxy impregnation and denser microstructure that is free of de-bonding cracking than the flat spacer-concrete interface. In addition, no carbonation was observed at the split spacer-concrete interface, while the interface between flat spacers and concrete were generally entirely carbonated.

Additionally, at equal w/b ratio (0.4), split spacers with exposed fibres were more effective for improving bond strength and permeability resistance than split spacers with reactive surfaces (with 80% slag), especially at 7d. Conversely, composite samples with reactive split spacers consistently showed higher diffusivity and sorptivity resistance than most samples with fibre-reinforced split spacers. Samples with polypropylene fibre reinforced split spacers were the only exception, which showed even lower diffusivity and sorptivity than samples with reactive split spacers made of 0.35 w/b ratio.

This research has, for the first time, carried out a fundamental investigation on the performance of various commercial cementitious spacers and their effects on concrete durability, which highlighted the need of a national guidance to regulate the properties of cementitious spacers used in the industry. Additionally, innovative methods for producing spacers with fibre reinforcement and reactive surfaces that could enhance the bonding between spacers and concrete were developed and evaluated. Bond strength, mass transport resistance and microstructure at the spacer-concrete interface were found to be improved substantially over conventional flat spacers, which will undoubtedly reduce the negative effects on concrete durability induced by spacers.

8.2 Recommendations for future research and policy/standards

8.2.1 Future research

Chapters 4 and 5 presented a study on the performance of some commercially available cementitious spacers and their effects on concrete durability. Although attempts were made to source as many different types of spacers as possible, the study was inevitably limited to products from manufacturers and suppliers based in the UK and nearby. There is a lack of global database, particularly the performance of cementitious spacers from countries with little/no guidance and regulations. Additionally, according to the test results, some spacers were already carbonated in the as-received condition. It is unclear whether and to what extent this is common in the industry. Clear carbonation depths were observed at locations that would be in direct contact with reinforcement. Therefore, it would be worth conducting a more thorough study on spacers obtained from other regions. It would also be important to establish the extent of which pre-carbonated spacers affect passivation of embedded reinforcement steel and resistance against reinforcement corrosion.

Chapter 6 proposed a potential method for enhancing spacer-concrete interface by fibre-reinforcement. Steel fibre was found to be less effective due to the low number of fibres exposed on spacer surfaces. It is impractical to further increase the dosage of steel fibre due to the negative impact on workability and increased ductility of such spacers. However, it is worth to try using steel fibres with smaller diameters in order to increase the number of exposed fibres at constant dosage. In addition, the orientation and distribution of fibres exposed on the spacer

surfaces are likely to influence the effectiveness of fibre-reinforced split spacers. Yet, this aspect was neither controlled nor quantified in this study. It would be interesting to develop practical methods for optimising the fibre arrangement and quantifying the effects of fibre orientation. The correlation between fibre orientation and distribution, and their contributions to enhance spacer-concrete interface could be better understood for achieving optimised design on fibre-reinforced spacers. Steel and glass fibres were found to be more beneficial in improving the bond strength and cracking resistance, while polypropylene fibres were more effective in enhancing mass transport resistance at spacer-concrete interface. Therefore it would also be interesting to develop spacers with hybrid fibre reinforcement.

Chapter 7 proposed a method to produce spacers with reactive surfaces and found that this successfully enhanced the spacer-concrete interface. One point worth further investigation is the effect of spacer curing time. Spacers produced in this study were all cured for 7d to maintain higher content of unreacted particles. However, it remains unknown if longer curing time would affect the effectiveness of such spacers. It is also helpful to understand the maximum curing/conditioning time before splitting the spacers and applying them in construction. In addition, materials for producing reactive spacers are not only limited to slag-blended cementitious materials. It is worth investigating the potential of other alkali-reactive materials such as fly ash and metakaolin, particularly those with high carbonation resistance.

Spacers with fibre reinforcement and reactive surfaces showed different effectiveness on enhancing the spacer-concrete interface from different aspects. Therefore it is predicted that hybrid spacers with both fibres and slag incorporation would achieve better bonding with concrete. The optimal mix composition might not be a simple combination of the individual optimal design, because other factors such as the effect of bleeding (caused by using high slag contents) on fibre distribution are worth evaluating.

In this study, the new developed spacers were simplified into half cylinder in order to facilitate the experimental characterisation and analysis. The spacer producing method proposed in this study need to be adjusted to produce well-shaped spacers that are practical for on-site use. This could include the design of initial spacer shapes (before splitting into individual spacers) for exposing fibres and unreacted particles, efficient methods for splitting spacers without inducing additional cracks and optimal individual spacer shape capable of achieving other requirements such as aesthetics and concrete compaction etc. These factors are likely to have an impact on the effectiveness of spacers, therefore there are worth to carefully design and evaluation.

Other methods for producing spacers with surfaces that could have better chemical or mechanical bonding with concrete is also worth investigating, such as grit blasting or water jetting the surfaces of spacers, the use of bonding agents and special coatings on the surfaces of spacers etc.

8.2.2 Policy/standards

Results from Chapters 4 and 5 showed that the performance of commercially available cementitious spacers is highly variable and on the whole, they induce negative effects on concrete durability. Therefore, further work is needed to raise the awareness on the manufacture, selection and usage of more durable spacers in concrete constructions. Actions that could benefit the bonding between spacer and concrete such as controlling the humidity of cementitious spacers and careful vibration and curing practices (to ensure good microstructure and bond development at the spacer-concrete interface) should also be suggested in relevant guidance or standards. Additionally, there is a need to develop more rigorous national guidance with regulations on specific durability properties (e.g. limiting values for mass transport), requirements for performance testing and assessment procedures for the spacer itself and concrete cover (with embedded spacers). More stringent requirements for manufacturers to provide the properties of their products and rules for the selection of spacers (depending on application, exposure environment and fire resistance requirements etc.) and quality inspection of spacers on site should also be introduced.

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Appendix I Preliminary survey of commercial cementitious spacers from representative manufacturers worldwide

Manufacturer	Sources	Material	Cover depth (mm)	Other dimensions (mm)	Weight (kg/pc)	Compressive strength (MPa)	Others
HY-TEN Ltd. (UK)	http://www.hy-ten.co.uk/accessories-spacers-concrete	Concrete	15-100			> 40	Coefficient of expansion and contraction similar to that of concrete.
Straight 2 Site Ltd. (UK)	https://straight2site.co.uk/c/reinforcement-spacers/concrete-spacers	Cement; 0/4mm sand; Aggregate: Cement=3:1	25-75			> 40	Dimensional tolerance < 5%
Plaka Ireland Ltd. (Ireland)	https://www.plaka-solutions.com/en/product-catalogue/reinforcement-spacers	Glass fibre reinforced concrete	20-75			50	Have been tested to ten times the load required under standard working practices.
BS Specialist Products Ltd. (UK)	https://www.corden-bssp.co.uk/project/reinforcement-accessories/	A blend of Portland cement, sand, coarse aggregates and additives	25-100			> 40	Dimensional tolerance: $\pm 5\%$
Euro Accessories Ltd. (UK)	https://www.euroacc.co.uk/bs-7973---1-2001	Cement; 0/4mm sand; Aggregate: Cement=3:1	20-80			> 40 or > 50	Dimensional tolerance < 5%

Appendix I Preliminary survey of commercial cementitious spacers from representative manufacturers worldwide (Continued)

Manufacturer	Sources	Material	Cover depth (mm)	Other dimensions (mm)	Weight (kg/pc)	Compressive strength (MPa)	Others
Max Frank GmbH & Co. KG (Germany)	https://www.maxfrank.com/intl-en/	Fibre reinforced concrete	15-100			> 50	Permitted deformation: <1mm; Water absorption: < 3% after 30 mins; Chloride diffusivity: < $0.5 \times 10^{-12} \text{ m}^2/\text{sec}$
Bartek systems k.s. Ltd. (Slovakia)	https://www.bartek.systems/store/c17/SPACE_RS_AND_TUBES.html	Fibre concrete	20-100	Thickness: 20-35	0.13-0.20	55	Compressive strength tested according to DIN 104 - part 5 on fibre concrete square profile $100 \times 100 \times 100 \text{ mm}^3$.
Nevoga Ltd. (Germany, Poland, Czechia, Austria)	https://www.nevoga.com/en/	Fibre concrete	20-100	Thickness: 15-40			Approved according to DBV specification
Molenaar north america inc. (US)	https://molenaar-americas.com/		25-50	Cross-sectional area: 45×80	0.20-0.40		Recommend to wet the spacers before using for improving bonding with concrete.

Appendix I Preliminary survey of commercial cementitious spacers from representative manufacturers worldwide (Continued)

Manufacturer	Sources	Material	Cover depth (mm)	Other dimensions (mm)	Weight (kg/pc)	Compressive strength (MPa)	Others
Guangzhou Zeli Ltd. (China)	http://www.cqzeli.com/?action=list 020zeli 1 cn 58356 58356&sortid=56661		20-180				
Beijing Jiali Ltd. (China)	http://www.jingjiajiancai.com/Product.asp		20-150				
Shanghai Life Ltd. (China and Japan)	http://www.sh-life.cn/page/cp/		20-150			2-12 kN (Ultimate load)	
Actech Ltd. (Australia)	http://www.actech.com.au/spacers		20-80		0.06-0.35	65	
Astra Ltd. (India)	https://www.astraconcrete.in/		15-100	Max rebar: Ø16-40		2.0-8.4 kN (Ultimate load)	

Appendix II Cover depths of commercial cementitious spacers (Unit: mm)

Spacer	S1	S2	S3	S4	S5	M1		M2		M3		M4	
						Cover 1	Cover 2	Cover 1	Cover 2	Cover 1	Cover 2	Cover 1	Cover 2
1	51.91	49.95	51.54	50.33	50.13	42.89	35.33	46.06	35.28	46.60	36.40	46.63	36.11
2	51.73	49.83	50.09	51.41	50.53	42.85	31.71	45.38	33.81	46.55	33.56	44.87	36.00
3	52.57	50.19	50.50	50.15	50.93	43.82	34.84	45.66	33.35	46.65	35.44	46.07	36.08
4	54.29	50.54	53.09	51.34	50.62	44.59	34.21	42.54	35.16	46.47	36.74	44.31	35.49
5	53.31	51.52	52.30	49.89	49.77	41.27	33.40	43.21	35.60	43.75	35.54	46.56	35.96
6	54.27	51.43	49.84	51.13	49.93	46.47	36.02	42.57	34.97	44.60	37.11	44.80	34.49
7	52.19	48.95	50.49	50.88	50.26	45.37	32.39	44.89	35.98	46.88	36.45	46.09	34.81
8	53.69	51.79	52.68	49.79	49.98	42.29	33.16	45.09	35.59	46.15	35.29	46.00	35.72
9	53.81	51.18	51.37	51.32	49.62	42.19	34.48	44.26	35.79	46.49	33.16	45.49	35.77
10	51.47	51.49	51.69	51.69	50.25	43.11	31.35	44.34	34.33	46.28	34.29	44.61	36.03
11	52.05	50.31	50.36	50.26	50.47	43.43	32.69	44.01	34.07	45.95	35.16	45.34	35.97
12	52.40	50.80	50.10	50.59	50.57	43.31	32.26	44.10	34.38	45.16	35.29	45.52	35.54
13	53.70	50.21	50.38	50.26	49.57	42.98	34.19	44.01	34.12	45.12	34.72	45.41	35.92
14	53.07	50.68	50.78	50.87	50.26	43.03	32.32	45.69	34.99	45.01	35.55	45.35	35.71
15	52.51	50.80	50.11	50.99	50.59	42.47	32.35	44.45	34.24	45.73	34.41	45.63	35.82
16	53.42	50.83	50.36	49.60	50.86	44.20	34.96	45.96	34.35	45.11	35.14	45.44	35.94
17	51.93	50.78	50.93	49.38	51.83	44.86	32.20	44.09	34.39	45.35	35.35	45.42	35.80
18	52.56	50.60	50.89	49.72	51.19	44.83	35.76	45.91	34.52	45.30	35.59	45.50	35.47
19	53.76	50.67	50.19	50.04	50.88	42.61	33.64	45.65	34.14	45.18	35.15	45.73	35.35
20	53.65	50.08	50.65	49.33	51.78	42.06	32.97	45.51	34.93	45.55	35.39	45.91	35.95
21	51.02	50.66	50.09	49.45	51.33	44.14	33.01	43.32	34.38	45.20	35.08	45.72	35.69
22	51.43	50.61	50.20	49.07	50.88	44.82	32.94	44.58	34.72	45.54	35.77	45.47	35.69
23	51.02	50.40	50.74	49.30	50.79	42.80	35.25	44.09	34.54	45.22	35.94	45.28	35.07
24	52.15	50.51	50.91	50.89	51.23	43.58	33.22	44.57	35.00	45.10	35.37	45.20	35.61
25	51.68	50.09	50.52	49.17	51.45	43.64	34.04	44.03	34.48	45.98	35.46	45.84	35.02

Appendix II Cover depths of commercial cementitious spacers (Unit: mm) (Continued)

Spacer	S1	S2	S3	S4	S5	M1		M2		M3		M4	
						Cover 1	Cover 2	Cover 1	Cover 2	Cover 1	Cover 2	Cover 1	Cover 2
26	51.99	50.55	50.75	49.95		44.24	34.29	43.86	34.76	45.62	34.05	45.87	35.57
27	51.54	50.71	50.87	50.68		42.21	33.84	43.57	34.65	45.45	34.53	45.30	35.51
28	51.11	50.96	50.72	49.63		42.66	35.11	44.47	34.15	45.79	34.25	45.64	35.49
29	53.93	50.65	50.69	49.85		43.83	35.89	45.20	34.91	45.85	34.51	45.58	35.80
30	53.18	50.01	50.08	50.56		43.70	34.02	44.60	34.23	45.36	35.08	45.75	35.40
31	51.76	50.52	50.01	50.80		43.16	35.16	43.20	34.70	45.73	34.64	45.10	35.67
32	52.10	50.13	50.83	49.91		44.53	33.54	43.08	34.37	45.80	34.11	45.82	35.05
33	53.28	50.25	50.39	49.49		44.84	32.18	43.54	34.68	45.50	35.04	45.99	35.03
34	51.75	50.41	50.42	50.39		44.56	31.45	45.98	34.12	45.29	34.71	45.40	35.43
35	52.87	50.50	50.87	50.08		42.23	33.39	44.59	34.02	45.89	35.14	45.14	35.07
36	53.47	50.16	50.50	49.13		42.21	31.41	44.34	34.50	45.30	34.99	45.50	35.70
37	52.86	50.30	50.38	49.17		43.98	35.72	43.37	34.11	45.53	35.61	45.09	35.92
38	51.92	50.19	50.47	49.88		42.03	33.56	45.03	34.01	45.12	34.55	45.06	35.25
39	52.79	50.82	50.11	49.54		43.91	31.54	45.01	34.48	45.72	35.02	45.33	35.70
40	53.68	50.29	50.88	50.52		43.15	34.92	45.93	34.85	45.94	35.86	45.64	35.54
41	51.21	50.63	50.38	49.35		44.07	33.21	45.37	34.51	45.43	35.52	45.15	35.27
42	51.57	50.46	50.42	49.24		44.96	31.02	43.59	34.09	45.22	35.95	45.20	35.64
43	53.29	50.58	50.53	50.93		42.99	35.83	43.76	34.56	45.24	34.39	45.05	35.21
44	53.92	50.53	50.03	49.70		43.97	31.78	44.76	34.07	45.77	35.11	45.40	35.53
45	51.66	50.05	50.16	49.43		44.34	34.50	43.22	34.81	45.08	34.13	45.94	35.23
46	52.08	50.94	50.45	50.82		42.96	34.29	43.42	34.48	45.49	34.15	45.94	35.14
47	52.80	50.04	50.97	49.53		44.79	32.87	45.64	34.63	45.50	35.18	45.72	35.19
48	53.06	50.41	50.76	50.84		44.05	33.70	44.26	34.29	45.84	34.69	45.14	35.31
49	52.49	50.72	50.66	49.46		43.97	33.42	43.68	34.28	45.86	35.00	45.48	35.91
50	53.71	50.71	50.93	50.80		43.52	33.34	45.39	34.93	45.84	34.03	45.43	35.18

Appendix III Compressive strength of commercial cementitious spacers

Sample	Replicate from each spacer	b (mm)				Mean (mm)	b' (mm)				Mean (mm)	h (mm)				Mean (mm)	Compressive Strength(MPa)
S1-1	1	14.81	14.97	14.95	14.89	14.91	14.95	14.87	14.89	14.84	14.89	14.88	14.86	14.84	14.94	14.88	36.32
	2	15.07	15.05	15.07	14.98	15.04	15.08	15.04	15.07	15.05	15.06	15.06	14.97	15.05	15.02	15.03	36.77
	3	14.80	14.87	14.91	14.81	14.85	14.87	14.86	14.88	14.93	14.89	14.91	14.91	14.80	14.80	14.86	36.88
	4	14.79	14.90	14.81	14.79	14.82	14.81	14.72	14.75	14.86	14.79	14.73	14.78	14.89	14.74	14.79	37.55
S1-2	1	14.96	15.04	14.95	14.95	14.98	15.08	15.02	14.98	15.07	15.04	14.98	15.03	15.05	14.98	15.01	38.95
	2	14.90	14.89	15.05	14.99	14.96	14.86	14.91	14.90	15.04	14.93	14.98	14.93	14.88	15.04	14.96	37.89
	3	14.97	14.98	14.94	15.03	14.98	14.93	14.94	15.02	14.99	14.97	15.00	14.95	14.91	14.99	14.96	38.48
	4	14.81	14.85	14.96	14.86	14.87	14.92	14.86	14.94	14.92	14.91	14.90	14.94	14.83	14.99	14.92	37.26
S1-3	1	14.94	14.90	14.87	15.05	14.94	14.99	14.87	14.88	14.94	14.92	14.88	15.05	15.01	14.86	14.95	37.33
	2	14.94	14.94	14.80	14.86	14.89	14.82	14.89	14.85	14.84	14.85	14.99	14.85	14.96	14.82	14.91	37.86
	3	14.86	14.91	14.85	14.77	14.85	14.93	14.88	14.82	14.93	14.89	14.78	14.83	14.90	14.90	14.85	37.05
	4	14.94	15.12	15.05	15.12	15.06	14.94	15.05	14.96	15.12	15.02	14.96	15.00	15.07	14.94	14.99	36.09
S2-1	1	14.91	14.85	14.87	14.81	14.86	14.87	14.84	14.75	14.78	14.81	14.84	14.90	14.86	14.89	14.87	30.67
	2	14.99	15.13	15.04	15.11	15.07	14.96	15.13	15.09	15.01	15.05	15.14	15.14	15.01	15.14	15.11	31.09
	3	15.03	14.95	14.96	15.01	14.99	14.97	14.98	14.98	15.05	15.00	14.97	14.94	14.88	15.00	14.95	31.06
	4	15.04	14.88	15.00	15.05	14.99	15.06	15.03	15.04	14.90	15.01	15.04	14.98	14.97	14.88	14.97	29.16
S2-2	1	14.90	14.90	14.85	14.88	14.88	14.95	14.85	14.94	14.89	14.91	14.97	14.88	14.97	14.89	14.93	29.70
	2	14.91	15.02	14.88	14.98	14.95	15.00	14.95	14.99	15.05	15.00	15.02	14.92	15.03	14.90	14.97	31.45
	3	14.96	14.99	14.95	14.81	14.93	14.82	14.93	14.87	14.99	14.90	14.80	14.92	14.91	14.86	14.87	30.07
	4	14.77	14.81	14.80	14.77	14.79	14.76	14.76	14.79	14.77	14.77	14.91	14.79	14.89	14.84	14.86	31.04
S2-3	1	15.04	14.97	15.06	15.02	15.02	15.05	14.97	15.10	15.07	15.05	14.94	15.10	15.04	15.09	15.04	31.32
	2	14.81	14.99	14.93	14.89	14.91	14.99	14.87	14.80	14.85	14.88	14.90	14.91	14.87	14.83	14.88	30.53
	3	14.96	14.92	14.93	15.01	14.96	14.92	15.09	15.02	14.93	14.99	15.02	15.08	15.07	15.06	15.06	31.14
	4	14.97	14.98	14.95	14.93	14.96	14.98	14.80	14.80	14.88	14.87	14.89	14.93	14.94	14.83	14.90	30.85

Appendix III Compressive strength of commercial cementitious spacers (Continued)

Sample	Replicate from each spacer	b (mm)				Mean (mm)	b' (mm)				Mean (mm)	h (mm)				Mean (mm)	Compressive Strength(MPa)
S3-1	1	15.02	14.90	15.06	15.02	15.00	15.00	15.06	14.92	14.89	14.97	15.06	14.92	14.89	14.94	14.95	36.52
	2	14.98	14.94	14.85	14.86	14.91	14.87	14.96	15.00	14.90	14.93	14.97	14.91	14.95	14.84	14.92	36.48
	3	14.88	14.93	14.88	14.88	14.89	15.04	15.03	14.91	14.88	14.97	15.04	14.86	15.05	14.87	14.96	36.48
	4	14.88	14.97	14.99	14.92	14.94	14.93	14.87	14.92	14.86	14.90	14.87	14.92	14.90	14.83	14.88	35.91
S3-2	1	14.94	14.86	14.79	14.77	14.84	14.75	14.91	14.80	14.80	14.82	14.77	14.86	14.80	14.94	14.84	34.93
	2	15.04	15.12	14.93	15.09	15.05	14.93	15.05	15.09	14.95	15.01	15.10	15.00	14.96	15.10	15.04	35.13
	3	14.88	14.89	14.95	14.97	14.92	14.95	14.88	14.86	14.96	14.91	14.92	14.94	14.88	14.81	14.89	35.01
	4	14.93	15.00	15.08	15.00	15.00	14.97	15.00	15.05	15.02	15.01	15.00	15.02	14.99	15.02	15.01	35.44
S3-3	1	14.93	14.84	14.97	14.92	14.92	14.90	14.84	14.82	14.88	14.86	14.79	14.81	14.94	14.86	14.85	36.37
	2	14.73	14.86	14.76	14.72	14.77	14.89	14.89	14.81	14.76	14.84	14.79	14.82	14.78	14.72	14.78	36.51
	3	15.02	15.13	15.10	14.96	15.05	15.07	15.04	14.98	15.12	15.05	14.95	15.05	15.13	14.96	15.02	36.15
	4	14.96	14.93	14.95	14.95	14.95	15.03	14.96	14.94	14.89	14.96	14.96	14.91	15.00	15.00	14.97	35.88
S4-1	1	14.92	14.96	14.90	14.85	14.91	14.85	14.80	14.92	14.97	14.89	14.85	14.97	14.86	14.98	14.92	31.32
	2	14.92	14.78	14.94	14.78	14.86	14.84	14.79	14.88	14.75	14.82	14.77	14.87	14.92	14.85	14.85	30.84
	3	15.00	15.01	15.09	14.96	15.02	14.95	15.09	14.99	14.95	15.00	14.95	15.10	14.93	15.05	15.01	30.78
	4	14.91	14.84	14.97	14.84	14.89	14.83	14.96	14.85	14.95	14.90	14.99	14.87	14.81	14.88	14.89	29.17
S4-2	1	15.04	15.11	15.05	15.10	15.08	15.01	14.95	14.99	15.09	15.01	15.03	15.01	14.97	14.98	15.00	30.45
	2	14.87	14.89	14.83	14.86	14.86	14.84	14.98	14.89	14.98	14.92	14.91	14.83	14.86	14.82	14.86	30.80
	3	14.85	14.87	14.81	14.79	14.83	14.91	14.82	14.89	14.72	14.84	14.73	14.86	14.85	14.77	14.80	30.86
	4	15.08	15.14	15.12	15.08	15.11	14.96	15.06	15.06	15.02	15.03	15.00	15.13	14.98	15.09	15.05	29.79
S4-3	1	14.91	14.98	15.03	14.97	14.97	15.04	14.87	14.90	14.93	14.94	15.04	14.88	14.98	15.03	14.98	29.92
	2	15.02	14.99	14.99	14.91	14.98	14.96	15.02	14.92	14.94	14.96	15.05	14.97	14.89	15.00	14.98	31.70
	3	14.88	14.93	14.83	14.81	14.86	14.83	14.87	14.97	14.81	14.87	14.83	14.82	14.84	14.97	14.87	30.09
	4	14.88	14.90	15.05	15.05	14.97	14.97	15.02	14.92	15.00	14.98	15.01	15.03	14.86	14.89	14.95	29.79

Appendix III Compressive strength of commercial cementitious spacers (Continued)

Sample	Replicate from each spacer	b (mm)				Mean (mm)	b' (mm)				Mean (mm)	h (mm)				Mean (mm)	Compressive Strength(MPa)
S5-1	1	14.97	14.87	14.83	14.95	14.91	14.98	14.82	14.91	14.80	14.88	15.00	14.84	14.91	14.86	14.90	36.54
	2	14.84	14.84	14.85	14.91	14.86	14.93	14.82	14.97	14.81	14.88	14.88	14.94	14.95	14.94	14.93	36.29
	3	14.96	14.79	14.83	14.92	14.88	14.84	14.79	14.89	14.95	14.87	14.87	14.91	14.81	14.82	14.85	36.89
	4	14.89	14.92	14.89	14.93	14.91	14.89	14.86	14.87	14.95	14.89	14.84	14.86	14.86	14.83	14.85	36.74
S5-2	1	14.78	14.83	14.74	14.81	14.79	14.86	14.71	14.84	14.73	14.79	14.83	14.87	14.74	14.74	14.80	37.63
	2	14.80	14.75	14.73	14.85	14.78	14.81	14.78	14.77	14.89	14.81	14.87	14.77	14.84	14.73	14.80	37.30
	3	14.86	14.73	14.76	14.77	14.78	14.78	14.89	14.88	14.90	14.86	14.89	14.88	14.73	14.73	14.81	37.32
	4	14.78	14.89	14.82	14.89	14.85	14.72	14.89	14.72	14.85	14.80	14.78	14.84	14.90	14.92	14.86	37.11
S5-3	1	14.80	14.81	14.82	14.82	14.81	14.81	14.89	14.75	14.81	14.82	14.84	14.85	14.73	14.74	14.79	37.35
	2	14.72	14.88	14.82	14.88	14.83	14.80	14.79	14.87	14.76	14.81	14.81	14.76	14.76	14.89	14.81	37.53
	3	14.81	14.82	14.83	14.78	14.81	14.75	14.81	14.80	14.75	14.78	14.78	14.82	14.82	14.70	14.78	37.67
	4	14.76	14.87	14.71	14.70	14.76	14.79	14.71	14.76	14.84	14.78	14.82	14.88	14.78	14.74	14.81	37.65
M1-1	1	15.09	15.13	15.18	15.13	15.13	15.04	15.15	15.19	15.02	15.10	15.20	15.02	15.15	15.04	15.10	41.39
	2	15.12	15.04	15.14	15.02	15.08	15.10	15.19	15.19	15.05	15.13	15.14	15.07	15.12	15.09	15.11	41.40
	3	15.06	15.02	15.01	15.03	15.03	15.05	15.11	15.07	15.06	15.07	15.01	15.12	15.14	15.12	15.10	40.30
	4	15.05	15.06	15.20	15.05	15.09	15.10	15.14	15.06	15.17	15.12	15.14	15.18	15.02	15.17	15.13	41.62
M1-2	1	14.91	15.06	14.98	15.09	15.01	15.05	14.97	14.90	14.99	14.98	15.06	15.06	14.90	15.00	15.01	42.41
	2	14.93	15.00	15.08	15.03	15.01	14.97	14.99	15.01	15.09	15.02	15.02	14.92	14.97	15.05	14.99	42.48
	3	14.92	15.09	15.03	14.90	14.99	15.06	14.99	15.05	15.06	15.04	15.06	14.96	15.01	14.91	14.99	42.39
	4	15.04	14.93	15.09	14.98	15.01	14.93	15.07	14.97	14.98	14.99	15.06	15.02	15.00	14.96	15.01	41.21
M1-3	1	15.00	14.94	14.96	14.96	14.97	14.95	14.97	14.93	14.97	14.96	14.96	15.00	14.94	14.91	14.95	42.96
	2	14.87	15.00	14.88	14.86	14.90	14.98	14.92	14.86	14.84	14.90	14.86	14.89	15.00	14.97	14.93	42.56
	3	14.90	14.87	14.83	15.00	14.90	14.98	14.82	14.96	14.91	14.92	14.97	14.94	14.84	14.83	14.90	42.16
	4	14.86	15.00	15.00	14.92	14.95	14.86	15.00	14.96	14.99	14.95	14.81	14.97	14.91	14.93	14.91	41.36

Appendix III Compressive strength of commercial cementitious spacers (Continued)

Sample	Replicate from each spacer	b (mm)				Mean (mm)	b' (mm)				Mean (mm)	h (mm)				Mean (mm)	Compressive Strength(MPa)
M2-1	1	15.30	15.14	15.18	15.20	15.21	15.25	15.14	15.29	15.17	15.21	15.22	15.17	15.23	15.23	15.21	33.98
	2	15.03	15.01	15.12	15.04	15.05	15.07	15.06	15.06	15.12	15.08	15.11	15.06	15.15	15.13	15.11	33.85
	3	15.12	15.22	15.17	15.11	15.16	15.26	15.17	15.10	15.13	15.17	15.14	15.21	15.09	15.13	15.14	34.72
	4	14.99	15.00	15.05	15.07	15.03	15.03	15.00	14.99	14.99	15.00	15.00	15.06	14.99	15.01	15.02	34.51
M2-2	1	14.98	14.98	14.97	14.90	14.96	15.03	14.98	14.97	15.04	15.01	15.08	14.92	14.91	14.98	14.97	32.70
	2	15.04	14.86	14.89	14.88	14.92	15.04	14.88	14.94	14.88	14.94	15.03	15.01	14.88	14.99	14.98	33.93
	3	15.11	15.05	15.06	14.99	15.05	15.05	15.11	15.01	15.11	15.07	15.02	15.11	15.01	15.11	15.06	32.67
	4	15.08	15.04	14.95	14.98	15.01	15.07	14.95	14.98	15.03	15.01	15.04	14.93	15.03	15.08	15.02	33.56
M2-3	1	15.09	15.04	15.05	14.98	15.04	15.06	15.03	15.06	15.08	15.06	14.96	15.13	14.98	15.01	15.02	32.63
	2	14.91	14.90	14.89	14.93	14.91	14.93	15.03	14.95	14.88	14.95	14.98	14.87	14.88	15.06	14.95	33.43
	3	14.97	14.93	15.01	14.97	14.97	14.97	15.07	15.03	14.98	15.01	14.93	14.94	14.97	14.98	14.96	32.48
	4	15.09	15.15	15.16	15.16	15.14	15.09	15.10	15.13	14.99	15.08	15.13	15.03	15.05	15.02	15.06	32.37
M3-1	1	15.16	15.24	15.23	15.14	15.19	15.09	15.06	15.14	15.23	15.13	15.07	15.21	15.19	15.15	15.16	35.11
	2	15.18	15.15	15.05	15.01	15.10	15.13	15.06	15.10	15.08	15.09	15.18	15.04	15.17	15.06	15.11	36.29
	3	15.02	15.13	15.06	15.11	15.08	15.11	15.00	15.09	15.03	15.06	15.04	15.06	14.98	14.96	15.01	35.89
	4	15.07	15.06	15.04	15.09	15.07	15.03	14.95	15.02	15.06	15.02	14.98	15.04	15.07	14.95	15.01	36.43
M3-2	1	14.91	15.00	15.05	15.03	15.00	15.03	15.05	14.96	14.94	15.00	14.89	15.00	14.90	14.97	14.94	37.09
	2	15.02	15.12	15.16	15.04	15.09	15.04	15.12	15.07	15.14	15.09	15.12	15.05	15.10	15.06	15.08	36.72
	3	14.95	14.98	15.00	15.02	14.99	15.02	14.91	14.92	14.92	14.94	14.97	15.03	14.91	14.90	14.95	37.55
	4	15.00	15.00	14.95	14.95	14.98	14.93	14.89	14.96	15.00	14.95	14.98	15.05	14.99	14.87	14.97	37.62
M3-3	1	15.07	14.91	15.07	15.08	15.03	15.05	14.98	14.97	15.00	15.00	15.05	14.98	14.99	15.01	15.01	37.78
	2	14.94	15.12	15.03	15.05	15.04	15.02	15.00	15.07	15.06	15.04	15.08	15.01	15.01	15.02	15.03	37.42
	3	14.96	14.85	14.99	14.89	14.92	14.91	14.88	14.96	14.99	14.94	14.99	14.94	14.87	14.86	14.92	36.97
	4	14.88	15.02	15.06	15.05	15.00	14.97	14.98	15.02	14.98	14.99	15.05	14.94	14.92	15.06	14.99	36.29

Appendix III Compressive strength of commercial cementitious spacers (Continued)

Sample	Replicate from each spacer	b (mm)				Mean (mm)	b' (mm)				Mean (mm)	h (mm)				Mean (mm)	Compressive Strength(MPa)
M4-1	1	15.12	15.24	15.09	15.21	15.17	15.07	15.16	15.22	15.11	15.14	15.12	15.17	15.22	15.11	15.16	37.85
	2	15.27	15.19	15.23	15.23	15.23	15.25	15.18	15.13	15.17	15.18	15.30	15.19	15.20	15.12	15.20	37.32
	3	15.09	15.18	15.11	15.12	15.13	15.04	15.10	15.06	15.21	15.10	15.05	15.04	15.11	15.13	15.08	38.35
	4	15.04	14.95	14.98	15.01	15.00	14.95	15.00	14.99	15.01	14.99	15.03	14.97	15.02	14.88	14.98	39.07
M4-2	1	14.92	15.08	15.05	14.97	15.01	14.96	15.07	15.07	15.02	15.03	14.91	14.91	14.99	14.99	14.95	39.37
	2	14.99	14.93	14.93	14.81	14.92	14.91	14.99	14.96	14.83	14.92	14.86	14.91	14.98	14.82	14.89	38.59
	3	14.95	14.88	14.95	14.85	14.91	14.83	14.94	14.99	14.87	14.91	14.83	14.89	14.96	14.85	14.88	38.38
	4	14.84	14.93	14.86	15.01	14.91	14.84	15.02	14.85	14.98	14.92	14.88	14.87	14.94	15.00	14.92	38.16
M4-3	1	15.17	15.03	15.16	15.10	15.12	15.11	15.17	15.01	15.08	15.09	15.05	15.07	15.14	15.04	15.08	37.52
	2	14.93	14.92	14.94	14.88	14.92	14.85	14.81	14.78	14.82	14.82	14.96	14.82	14.90	14.80	14.87	39.46
	3	15.02	14.92	14.88	14.99	14.95	14.97	14.95	14.89	14.84	14.91	14.89	15.02	14.89	14.85	14.91	38.27
	4	15.13	15.13	15.14	15.10	15.13	15.13	15.06	15.12	15.01	15.08	15.09	15.10	15.00	15.16	15.09	37.66

Appendix IV Modulus of rupture of commercial cementitious spacers

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
S1-1	1	5.00	4.95	4.98	4.87	4.93	4.90	6.14
	2	4.89	5.03	4.96	4.91	5.06	4.99	6.05
	3	4.88	4.90	4.89	4.97	4.95	4.96	6.52
	4	5.00	4.97	4.99	4.92	4.95	4.94	6.24
	5	5.04	5.02	5.03	5.03	5.02	5.03	6.12
	6	5.06	4.94	5.00	5.05	4.92	4.99	6.01
S1-2	1	4.88	5.03	4.96	4.98	5.00	4.99	6.24
	2	4.98	4.93	4.96	5.00	5.06	5.03	6.09
	3	5.06	4.98	5.02	4.93	5.02	4.98	6.26
	4	4.88	5.02	4.95	5.01	4.88	4.95	6.49
	5	5.04	4.97	5.01	4.87	4.99	4.93	6.27
	6	5.05	4.88	4.97	4.90	5.05	4.98	6.27
S1-3	1	4.99	4.95	4.97	4.91	4.96	4.94	6.33
	2	4.89	4.89	4.89	5.06	5.03	5.05	6.29
	3	4.91	4.93	4.92	4.88	4.87	4.88	6.60
	4	4.90	4.96	4.93	4.99	4.87	4.93	6.58
	5	5.06	5.02	5.04	4.99	5.00	5.00	6.19
	6	4.93	4.87	4.90	5.01	5.03	5.02	6.10
S2-1	1	4.99	4.96	4.98	4.99	5.02	5.01	4.97
	2	5.00	4.89	4.95	4.95	4.97	4.96	4.81
	3	4.93	5.06	5.00	5.01	5.01	5.01	4.65
	4	4.92	4.89	4.91	4.89	4.92	4.91	4.93
	5	4.99	5.01	5.00	4.92	4.94	4.93	4.94
	6	4.97	4.99	4.98	4.99	4.90	4.95	4.84

Appendix IV Modulus of rupture of commercial cementitious spacers (Continued)

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
S2-2	1	4.90	4.90	4.90	4.94	4.88	4.91	4.91
	2	4.99	4.98	4.99	4.96	4.94	4.95	4.61
	3	4.91	4.96	4.94	5.04	5.01	5.03	4.61
	4	4.89	4.88	4.89	4.89	4.94	4.92	4.76
	5	4.88	4.94	4.91	5.04	4.94	4.99	4.69
	6	4.98	5.02	5.00	5.05	5.05	5.05	4.44
S2-3	1	4.94	4.92	4.93	5.01	4.98	5.00	4.81
	2	5.05	4.99	5.02	4.99	4.93	4.96	4.84
	3	5.04	5.04	5.04	5.04	4.88	4.96	4.65
	4	4.91	4.89	4.90	5.00	5.01	5.01	4.74
	5	4.87	4.97	4.92	5.00	5.00	5.00	4.68
	6	4.95	4.87	4.91	4.99	5.00	5.00	4.57
S3-1	1	4.88	4.89	4.89	4.83	4.94	4.89	5.59
	2	4.82	4.88	4.85	4.81	4.92	4.87	5.77
	3	4.88	4.88	4.88	5.00	4.92	4.96	5.67
	4	4.86	4.96	4.91	4.92	4.97	4.95	5.65
	5	4.95	4.86	4.91	4.86	4.98	4.92	5.78
	6	4.81	4.98	4.90	4.83	4.82	4.83	6.03
S3-2	1	4.91	4.97	4.94	4.92	4.93	4.93	5.78
	2	4.81	4.94	4.88	4.97	4.83	4.90	5.91
	3	5.00	4.99	5.00	4.83	4.86	4.85	5.89
	4	4.98	4.83	4.91	4.82	4.92	4.87	5.91
	5	5.00	4.99	5.00	4.85	4.85	4.85	5.99
	6	4.85	4.93	4.89	4.87	4.91	4.89	6.07

Appendix IV Modulus of rupture of commercial cementitious spacers (Continued)

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
S3-3	1	4.87	4.86	4.87	4.85	4.91	4.88	5.73
	2	4.81	4.81	4.81	4.98	4.93	4.96	5.87
	3	4.96	4.87	4.92	4.85	4.94	4.90	5.64
	4	4.96	4.99	4.98	4.89	4.89	4.89	5.68
	5	4.90	4.93	4.92	4.92	4.87	4.90	5.78
	6	4.89	4.85	4.87	4.95	4.82	4.89	5.92
S4-1	1	5.02	5.01	5.02	4.94	5.01	4.98	4.34
	2	5.05	5.10	5.08	4.97	5.02	5.00	4.51
	3	5.02	5.01	5.02	4.95	5.06	5.01	4.35
	4	4.99	5.09	5.04	5.11	5.07	5.09	4.13
	5	4.95	4.97	4.96	5.04	5.12	5.08	4.39
	6	4.94	5.05	5.00	4.96	4.99	4.98	4.50
S4-2	1	4.97	4.95	4.96	4.95	4.97	4.96	4.10
	2	4.93	4.95	4.94	4.93	5.00	4.97	4.27
	3	5.01	5.11	5.06	5.06	5.08	5.07	4.18
	4	5.05	4.97	5.01	5.05	5.01	5.03	4.11
	5	5.03	5.06	5.05	4.97	5.04	5.01	4.07
	6	5.11	4.99	5.05	4.99	5.06	5.03	4.02
S4-3	1	5.05	5.11	5.08	5.09	4.93	5.01	3.98
	2	5.01	4.94	4.98	4.96	4.93	4.95	4.04
	3	5.07	4.93	5.00	4.96	4.96	4.96	4.17
	4	5.08	5.01	5.05	5.01	4.93	4.97	4.05
	5	5.02	4.99	5.01	4.97	4.99	4.98	4.25
	6	4.94	5.02	4.98	5.02	5.00	5.01	4.22

Appendix IV Modulus of rupture of commercial cementitious spacers (Continued)

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
S5-1	1	4.96	5.01	4.99	4.97	5.05	5.01	6.91
	2	5.05	4.96	5.01	4.97	4.96	4.97	6.90
	3	5.02	4.99	5.01	4.98	4.97	4.98	6.85
	4	4.96	4.98	4.97	5.01	4.96	4.99	6.88
	5	5.00	5.04	5.02	5.00	4.96	4.98	6.84
	6	5.03	4.97	5.00	5.00	4.98	4.99	6.82
S5-2	1	4.96	4.98	4.97	4.96	5.00	4.98	6.85
	2	5.01	4.96	4.99	5.01	5.03	5.02	6.78
	3	4.97	5.04	5.01	5.04	4.99	5.02	6.76
	4	4.96	5.03	5.00	4.96	4.96	4.96	7.03
	5	5.03	5.03	5.03	5.03	5.05	5.04	6.67
	6	4.98	4.97	4.98	5.03	4.96	5.00	6.81
S5-3	1	4.96	5.03	5.00	4.96	4.97	4.97	6.92
	2	5.05	5.03	5.04	4.98	4.96	4.97	6.81
	3	4.99	4.98	4.99	5.00	4.98	4.99	6.85
	4	5.04	5.05	5.05	4.98	4.98	4.98	6.78
	5	4.99	5.01	5.00	4.99	5.00	5.00	6.83
	6	4.97	4.99	4.98	5.01	4.99	5.00	6.78
M1-1	1	5.02	4.98	5.00	4.96	4.98	4.97	7.68
	2	4.94	4.86	4.90	4.97	5.01	4.99	7.81
	3	4.94	4.88	4.91	5.02	5.02	5.02	7.62
	4	5.00	4.87	4.94	4.89	5.04	4.97	7.59
	5	4.94	4.91	4.93	4.89	5.02	4.96	7.60
	6	5.05	5.04	5.05	4.90	4.99	4.95	7.48

Appendix IV Modulus of rupture of commercial cementitious spacers (Continued)

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
M1-2	1	5.05	4.99	5.02	4.92	4.98	4.95	7.45
	2	4.87	4.98	4.93	5.05	5.04	5.05	7.16
	3	4.88	4.96	4.92	4.92	5.05	4.99	7.26
	4	5.00	5.05	5.03	4.96	4.97	4.97	7.14
	5	4.95	5.01	4.98	4.96	4.88	4.92	7.35
	6	5.03	4.89	4.96	4.98	4.96	4.97	7.05
M1-3	1	4.97	4.95	4.96	5.03	4.93	4.98	7.15
	2	4.93	4.95	4.94	4.93	4.93	4.93	7.30
	3	5.04	4.92	4.98	4.98	4.88	4.93	7.14
	4	4.93	5.05	4.99	5.03	5.02	5.03	6.97
	5	4.92	5.05	4.99	4.98	4.95	4.97	7.27
	6	4.88	5.02	4.95	4.93	5.03	4.98	7.09
M2-1	1	4.89	4.95	4.92	5.01	4.98	5.00	5.71
	2	5.03	4.90	4.97	4.90	4.86	4.88	5.97
	3	5.05	4.94	5.00	4.97	4.86	4.92	5.68
	4	5.05	4.90	4.98	5.03	5.00	5.02	5.57
	5	4.87	5.03	4.95	4.90	4.95	4.93	5.71
	6	4.90	4.86	4.88	5.04	4.96	5.00	5.69
M2-2	1	5.05	4.97	5.01	4.96	5.01	4.99	5.55
	2	4.94	4.87	4.91	5.02	5.04	5.03	5.51
	3	4.89	5.04	4.97	4.88	5.04	4.96	5.74
	4	5.03	5.03	5.03	4.94	5.01	4.98	5.65
	5	4.98	5.03	5.01	4.86	4.97	4.92	5.72
	6	4.94	4.99	4.97	5.03	5.05	5.04	5.39

Appendix IV Modulus of rupture of commercial cementitious spacers (Continued)

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
M2-3	1	4.95	4.94	4.95	4.91	5.03	4.97	5.88
	2	4.89	4.99	4.94	4.88	4.96	4.92	5.96
	3	4.97	4.91	4.94	4.90	4.97	4.94	5.70
	4	4.90	4.96	4.93	4.89	5.03	4.96	5.63
	5	5.02	4.98	5.00	5.03	5.05	5.04	5.50
	6	5.04	5.00	5.02	4.91	5.03	4.97	5.55
M3-1	1	4.97	5.01	4.99	4.99	4.95	4.97	5.99
	2	4.97	5.00	4.99	5.05	4.89	4.97	6.03
	3	5.02	4.98	5.00	5.04	5.06	5.05	5.90
	4	5.03	4.90	4.97	4.93	5.02	4.98	6.06
	5	4.91	4.95	4.93	4.92	4.93	4.93	6.19
	6	5.02	4.98	5.00	4.97	5.03	5.00	5.95
M3-2	1	4.92	5.05	4.99	5.00	4.91	4.96	6.00
	2	5.01	5.02	5.02	4.95	4.94	4.95	6.11
	3	4.92	5.05	4.99	5.07	4.94	5.01	6.02
	4	4.96	4.93	4.95	5.04	5.06	5.05	5.97
	5	5.04	5.07	5.06	5.06	5.03	5.05	5.63
	6	5.04	5.00	5.02	5.00	4.94	4.97	5.94
M3-3	1	4.92	4.92	4.92	4.99	4.90	4.95	6.06
	2	5.00	5.03	5.02	4.88	5.05	4.97	5.87
	3	5.06	5.01	5.04	4.90	5.02	4.96	5.75
	4	4.90	5.02	4.96	4.98	4.91	4.95	5.96
	5	4.91	4.98	4.95	4.96	4.95	4.96	6.01
	6	4.96	4.89	4.93	5.00	4.92	4.96	6.02

Appendix IV Modulus of rupture of commercial cementitious spacers (Continued)

Spacer	Replicate from each spacer	b (mm)		Mean (mm)	d (mm)		Mean(mm)	Modulus of rupture (MPa)
M4-1	1	5.01	4.87	4.94	4.96	4.97	4.97	4.99
	2	4.92	4.99	4.96	5.00	5.03	5.02	5.05
	3	4.85	4.91	4.88	5.02	4.96	4.99	5.14
	4	4.96	4.91	4.94	4.96	5.00	4.98	5.07
	5	4.85	4.98	4.92	4.86	4.97	4.92	5.24
	6	4.90	4.99	4.95	4.86	4.91	4.89	5.25
M4-2	1	4.91	4.88	4.90	4.98	4.99	4.99	5.12
	2	5.01	4.95	4.98	5.00	4.94	4.97	4.98
	3	4.87	4.86	4.87	4.86	5.02	4.94	5.35
	4	4.98	5.01	5.00	4.87	4.88	4.88	5.11
	5	4.87	4.89	4.88	4.87	4.89	4.88	5.36
	6	5.03	4.95	4.99	4.99	4.93	4.96	5.07
M4-3	1	4.93	4.95	4.94	5.00	5.03	5.02	5.02
	2	4.96	4.88	4.92	5.02	4.88	4.95	5.27
	3	4.89	4.89	4.89	4.87	4.91	4.89	5.37
	4	4.84	4.89	4.87	4.98	5.00	4.99	5.07
	5	4.89	5.01	4.95	4.84	4.93	4.89	5.19
	6	5.00	4.85	4.93	4.97	4.86	4.92	5.08

Appendix V Bond strength between slag-based spacer and concrete

Curing time (d)	7				14				28				91			
Spacers contained	Flat		Split		Flat		Split		Flat		Split		Flat		Split	
S0(0.35)	2.0	2.1 (0.03)	3.1	3.4 (0.34)	2.2	2.1 (0.11)	4.3	4.2 (0.09)	2.1	2.4 (0.22)	5.1	4.8 (0.32)	2.3	2.5 (0.21)	5.1	4.9 (0.25)
	2.1		3.6		2.1		4.1		2.4		4.5		2.4		4.7	
	2.1		3.0		2.2		4.2		2.5		4.5		2.8		4.6	
	2.1		3.7		2.0		4.2		2.6		5.0		2.4		5.1	
S60(0.35)	2.0	2.0 (0.05)	3.0	3.0 (0.13)	3.9	4.0 (0.09)	4.5	4.4 (0.15)	4.2	4.2 (0.14)	4.8	4.9 (0.15)	4.3	4.3 (0.09)	5.1	5.1 (0.16)
	2.0		3.2		4.1		4.3		4.1		4.9		4.3		5.0	
	2.1		3.0		4.0		4.6		4.0		4.8		4.2		5.3	
	2.0		3.0		3.9		4.4		4.3		5.1		4.2		5.0	
S80(0.35)	2.6	2.8 (0.13)	3.0	3.0 (0.18)	4.4	4.4 (0.16)	4.4	4.6 (0.12)	4.9	4.8 (0.20)	4.9	5.1 (0.47)	5.4	5.0 (0.29)	5.2	5.2 (0.17)
	2.7		2.9		4.2		4.6		4.9		5.8		4.9		5.1	
	2.9		3.3		4.6		4.7		4.5		4.9		4.7		5.2	
	2.8		2.9		4.3		4.6		4.8		4.8		4.9		5.5	
S0(0.4)	1.9	2.1 (0.10)	3.2	3.1 (0.16)	2.1	2.2 (0.04)	3.4	3.4 (0.13)	2.5	2.4 (0.07)	3.9	3.9 (0.04)	2.4	2.4 (0.14)	4.1	4.1 (0.07)
	2.1		2.9		2.1		3.3		2.5		3.9		2.4		4.1	
	2.2		3.3		2.2		3.6		2.3		3.9		2.6		4.0	
	2.1		3.2		2.2		3.4		2.5		4.0		2.2		4.0	
S80(0.4)	2.1	2.0 (0.08)	3.0	2.9 (0.09)	2.2	2.1 (0.03)	3.6	3.6 (0.06)	2.4	2.4 (0.08)	4.0	4.0 (0.16)	2.4	2.3 (0.16)	4.2	4.2 (0.05)
	1.9		2.8		2.1		3.7		2.5		4.0		2.3		4.1	
	2.0		2.9		2.1		3.6		2.4		4.2		2.5		4.2	
	2.0		2.8		2.1		3.5		2.3		3.8		2.2		4.2	
None	5.1	5.0 (0.14)			5.3	5.5 (0.19)			5.6	5.8 (0.18)			6.2	6.1 (0.12)		
	4.8				5.7				6.1				6.1			
	5.1				5.5				5.9				6.0			
	5.1				5.5				5.8				5.9			

Note: Unit of values is MPa; Standard deviation is marked in brackets; Type of spacers marked as none refers to cylinders made of concrete (C0.4).

Appendix VI Copyright permissions

Type of work:	Name of work	Source of work	Copyright holder and contact	permission requested on	I have permission yes /no	Permission note
Figure	Figure 2.1 Typical types of spacers	Influence of reinforcement spacers on mass transport properties and durability of concrete structures - Cement and Concrete Research (2016), vol 87, pp 31-44.	© 2016 Elsevier Ltd.	24.05.22	Yes	Licensed (License number: 5315261392653)
	Figure 2.6 Backscattered electron images of spacer-concrete interface					
	Figure 5.4 S spacer (marked in red) used by Alzyoud et al. (2016)					
	Figure 6.20 Porous interface between commercial cementitious spacer and concrete from previous research (Alzyoud et al., 2016)					
Figure	Figure 2.2 Spacers and chairs for: (a) bottom reinforcement; (b) top reinforcement in slabs (Unit: mm)	BS 7973-2: 2001 Spacers and chairs for steel reinforcement and their specification. Fixing and application of spacers and chairs and tying of reinforcement	© BSI 16 October 2001 copyright@bsigroup.com	24.05.22	Yes	Got a permission confirmation via email.
	Figure 2.3 Spacers used in beams: (a) elevation; (b) cross-section; (c) cross-section of deep beam (Unit: mm)					
	Figure 2.4 Spacers used in columns (Unit: mm)					
Figure	Figure 2.5 Corrosion at the interface between mortar spacer and concrete	A field study of critical chloride content in reinforced concrete with blended binder - Materials and Corrosion (2009), vol. 60, pp 617-622.	© 2009 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim	24.05.22	Yes	Licensed (License number: 5315280990234)
Figure	Table 2.3 Comparison of bond strength test methods	Bond strength of whitetoppings and bonded overlays constructed with self-compacting high-performance concrete - Construction and Building Materials (2017), vol. 153, pp 835-845.	© 2017 Elsevier Ltd.	24.05.22	Yes	Licensed (License number: 5315290887620)

Appendix VII Publications arising from this research

Journal papers

1. X. Chen, H.S. Wong, N.R. Buenfeld, Fundamental investigation on the performance of commercial cementitious spacers and their effects on concrete durability. (In preparation).
2. X. Chen, H.S. Wong, N.R. Buenfeld, Innovative fibre-reinforced spacers for improving bonding and durability of spacer-concrete interface (In preparation).
3. X. Chen, H.S. Wong, N.R. Buenfeld, Enhancing bond strength, mass transport properties and microstructure of spacer-concrete interface with surface reactive spacers. (In preparation).