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***EFFECT OF MINERAL ADDITIONS ON THE DURABILITY OF
REPAIR MORTARS IN HOT CLIMATE***

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Dedications

I dedicate this modest work to:

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Abstract

The aim of this work is to study the effect of supplementary cementitious materials (SCMs) as marble powder (MP) on the performance of self-compacting repair mortars (SCRM) reinforced with polypropylene fibres (PPF). Two series of mortars (PPF and PPF+ MP) were prepared and evaluated. Previously, an optimisation of fibre dosage in terms of fresh and hardened states was assessed, then incorporating MP as cement replacement. The evaluation of repair mortars was carried out on rheological properties (slump flow, flow time, yield stress and plastic viscosity), fresh density and mechanical strength (compressive and flexural strength). In addition to elasticity modulus), thermal conductivity, shrinkage and durability properties (mercury intrusion porosity) and capillary absorption. Moreover, the effect of hot-dry climate was evaluated on adhesion strength between repair mortar and substrate concrete. Three bond strength test methods were assessed on composite specimens (repair mortar/substrate material) conserved in two conditions (standard climate $T=20\pm 2^{\circ}\text{C}$, $\text{RH}= 30\%$ and real hot climate $T=40\pm 5^{\circ}\text{C}$, $\text{RH}= 10\%$). The obtained results revealed that, 0.06% of PPF is the optimum dosage with the highest compressive strength and good flexural strength. The introduction of MP decreases both plastic viscosity and yield stress. The combined use of PPF and MP showed good mechanical properties of SCRM which fulfilling the requirements of class R4 materials for structural repair products. Moreover, incorporating MP to fibre reinforced repair mortar increases its thermal conductivity compared to control mortar and reduces considerably porosity rate. On the other side, elasticity modulus has decreased with the increment of MP content however, a good correlation is attained between elasticity modulus and compressive strength. Adhesion test by slant shear method indicated that 15% of MP is the optimum dosage which provides 20% of gain in adhesion strength.

Keywords: Fibre reinforced mortar, self-compacting repair mortar, marble powder, rheological properties, adhesion bond strength, hot climate.

Résumé

L'objectif de ce travail est d'étudier l'effet des additions cimentaires (SCMs), en particulier la poudre de marbre (PM), sur les performances des mortiers de réparation auto-plaçants (SCRMs) renforcés par des fibres de polypropylène (PPF). Deux séries de mortiers (PPF et PPF + PM) ont été préparées et évaluées. Au préalable, une optimisation du dosage en fibres a été réalisée en termes d'états frais et durcis, puis l'incorporation de la PM en substitution du ciment a été étudiée. L'évaluation des mortiers de réparation a porté sur les propriétés rhéologiques (étalement au cône d'Abrams, temps d'écoulement, contrainte de seuil et viscosité plastique), la masse volumique à l'état frais et les résistances mécaniques (résistances à la compression et à la flexion). En plus du module d'élasticité, la conductivité thermique, le retrait et les propriétés de durabilité (porosité par intrusion de mercure) ainsi que l'absorption capillaire ont été étudiés. De plus, l'effet d'un climat chaud et sec a été évalué sur la résistance d'adhérence entre le mortier de réparation et le béton support. Trois méthodes d'essai d'adhérence ont été appliquées sur des éprouvettes composites (mortier de réparation/matériau de support) conservées dans deux conditions (climat standard $T = 20 \pm 2$ °C, HR = 30 % et climat chaud réel $T = 40 \pm 5$ °C, HR = 10 %). Les résultats obtenus ont révélé que 0,06 % de PPF constitue le dosage optimal, offrant la plus grande résistance à la compression et une bonne résistance à la flexion. L'introduction de la PM diminue à la fois la viscosité plastique et la contrainte de seuil. L'utilisation combinée de PPF et PM a montré de bonnes propriétés mécaniques du SCRM, répondant aux exigences des matériaux de classe R4 pour les produits de réparation structurelle. Par ailleurs, l'incorporation de PM dans les mortiers de réparation fibrés augmente leur conductivité thermique par rapport au mortier témoin et réduit considérablement le taux de porosité. En revanche, le module d'élasticité diminue avec l'augmentation du taux de PM, toutefois une bonne corrélation est obtenue entre le module d'élasticité et la résistance à la compression. L'essai d'adhérence par la méthode du cisaillement oblique a montré que 15 % de PM constitue le dosage optimal, permettant un gain de 20 % en résistance d'adhérence.

Mots clés : Mortier renforcé par fibre, mortier autoplaçant de réparation, poudre de marbre, paramètre rhéologique, résistance d'adhésion, climat chaud.

المخلص

الهدف من هذا العمل هو دراسة تأثير الإضافات الأسمنتية ، (SCMs) وبشكل خاص مسحوق الرخام ، (PM) على أداء المونة ذاتية الدمك المخصصة لأعمال الترميم (SCRMs) والمسلحة بالألياف البوليه بروبيلين (PPF). تم تحضير وتقييم سلسلتين من المونات (PPF و PM + PPF). في البداية، أُجريت عملية تحسين لجرعة الألياف من حيث الخصائص في الحالة الطازجة والمتصلية، ثم تمت دراسة دمج مسحوق الرخام كبديل جزئي عن الأسمنت. وقد شمل تقييم المونات المرممة الخصائص الريولوجية (الانتشار بواسطة مخروط أبرامز، زمن الانسياب، إجهاد الخضوع واللزوجة البلاستيكية)، الكثافة في الحالة الطازجة والمقاومات الميكانيكية (مقاومة الضغط والانحناء). بالإضافة إلى ذلك، تم دراسة معامل المرونة، الموصلية الحرارية، الانكماش وخصائص المتانة (المسامية عبر اختراق الزئبق) وكذلك الامتصاص الشعري. علاوة على ذلك، تم تقييم تأثير المناخ الحار والجاف على مقاومة الالتصاق بين المونة المرممة والخرسانة الحاملة. وقد طُبقت ثلاث طرق اختبار للالتصاق على عينات مركبة (مونة الترميم/خرسانة حاملة) محفوظة في شرطين مختلفين (مناخ قياسي $T=20\pm 2$ °م ، $RH=30\%$ ومناخ حار واقعي $T=40\pm 5$ ، $RH=10\%$). أظهرت النتائج أن نسبة 0.06% من ألياف PPF تُعد الجرعة المثلى، إذ تمنح أعلى مقاومة للضغط ومقاومة جيدة للانحناء. كما أن إدخال مسحوق الرخام يقلل من كل من اللزوجة البلاستيكية وإجهاد الخضوع. وقد بيّن الاستخدام المشترك لـ PPF و PM خصائص ميكانيكية جيدة للمونة ذاتية الدمك المرممة، مستوفية لمتطلبات مواد الفئة R4 الخاصة بمنتجات الترميم الإنشائي. من جهة أخرى، أدى دمج مسحوق الرخام في المونات المسلحة بالألياف إلى زيادة الموصلية الحرارية مقارنة بالمونة المرجعية، مع خفض ملحوظ لمعدل المسامية. بالمقابل، ينخفض معامل المرونة مع زيادة نسبة مسحوق الرخام، إلا أن علاقة جيدة ظهرت بين معامل المرونة ومقاومة الضغط. أما اختبار الالتصاق بطريقة القص المائل فقد أظهر أن نسبة 15% من مسحوق الرخام تمثل الجرعة المثلى، حيث تحقق زيادة قدرها 20% في مقاومة الالتصاق.

الكلمات المفتاحية : مونة مسلحة بالألياف، مونة ترميم ذاتية الدمك، مسحوق الرخام، معامل ريولوجي، مقاومة الالتصاق، مناخ حار.

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List of abbreviations

SCMs	Supplementary cementitious materials
MP	Marble powder
SCRMs	Self-compacting repair mortars
SCFRMs	Self-compacting fibre-reinforced repair mortars
RM	Repair mortar
SCC	Self-compacting concrete
PPF	Polypropylene fibres
T	Temperature
RH	Relative humidity
C	Cement
S	Sand
G	Gravel
W	Water
W/B	Water to binder ratio
C/S	Sand to cement ratio
SP	Superplasticizer
C1	Cement used in the formulation of self-compacting repair mortars
C2	Cement used in the formulation of substrate mortar and concrete
S1	Sand used in the formulation of repair mortar
S2	Sand used in the formulation of substrate materials
Γ_m	Relative spread
ITZ	Interfacial transition zone
FT	Flow time
SF	Slump flow
ρ	Fresh bulk density
λ	Thermal conductivity coefficient
σ_f	Flexural strength
σ_c	Compressive strength
E_D	Elasticity modulus
τ	Slant shear strength
S	Sorptivity coefficient
M	The total torque applied to the concrete
M_0	The torque at the origin.
k	Linear regression coefficient.
Ω	Angular torque speed of the vane
τ	Shear stress.
τ_0	Yield stress.
μ	Plastic viscosity.
$\dot{\gamma}$	Shear rate
Φ^*	Compacité de la pâte
Φ	Concentration volumique solide dans la pâte
Φ / Φ^*	Concentration solide relative dans la pâte
Δs	Shrinkage value
MIP	Mercury intrusion porosity

General introduction

General introduction

Concrete structures exposed to harsh conditions or had execution mistakes would require repairing and maintenance in order to ensure the preservation of its integrity. Concrete damage is caused through several factors such as change in function, increase in loads, changes in the building regulations and sometimes the mistakes in execution or chemical attacks [1–4]. In addition to that, the damage caused by fire, earthquake and any other deterioration resulting from a natural or human phenomenon otherwise from ageing of the structure and weathering actions.

The suitable solution in this situation is to repair or reinforce the structures rather than demolish and rebuild them. At present, a range of repair materials appears; polymer based mortars [5], lime repair mortars [6] and cementitious repair mortar [7]. Selecting repair material necessitates the understanding of its behaviour [8]. The crucial factor in selecting proper materials is their compatibility with the substrate which is determined by adhesion strength, similar dilatation properties, capillary water absorption and their durability [9,10].

Conventional cementitious repair mortars made using cements and sand are still giving attention due to its good adhesion to the existing concrete structure in terms of engineering and performance properties. In addition, its sustainability in different environment, cost and appearance [11].

The durability of repair materials and repaired structures is also essential to ensure a suitable lifespan for the repaired works. Consequently, the performance of repair materials should be evaluated under various environmental conditions to select the most efficient materials for the specified condition.

Algeria is characterized by a hot climate in the North during summer, and hot-dry conditions in the South. This type of environment is known for its harmful effect on concrete in general and on hydraulic binder-based materials [12].

Algeria is one of the countries with a vast marble rock deposit and huge amounts of marble waste that are little or not exploited in the construction field. Algeria has two marble deposits: the Fil-Fila deposit in Skikda, located in the northeast of Algeria, which is considered the largest in Africa, and the Silet deposit in Tamanrasset, which has been recently exploited. The Silet deposit, stretching over a 100 km strip, contains high-quality marble in various colours (white, blue, and green).

General introduction

The use of marble waste is highly necessary, on the one hand to prevent environmental pollution and on the other hand to protect and preserve natural resources that are heavily consumed by cement plants. Recycling marble waste in concrete production is very advantageous in terms of cost, durability, and ecology [13].

Marble powder (MP) as an inert filler can be successfully utilised to replace cement in mortar and concrete and has proved to have economic and environment advantages [14]. Several researchers in recent years have been used marble waste in concrete. Thus, recycling marble scrap powder has multiple positive effects [15–19].

For the purpose of enhancing the ductility and toughness of cementitious materials and its precracking behaviour the use of fibre is indispensable and has numerous important effects. Synthetic polypropylene fibres are usually used in repair applications. Thanks to their flexible nature, they are randomly distributed into the matrix and help limit and delay cracks openings due to the bridging effect. A considerable number of researchers reported that adding polypropylene fibres (PPF) showed a significant gain in hardened properties and toughness of cementitious materials [20,21]. The addition of fibres to reinforce repair materials have gained recently more attention [22,23]. Some researchers studied the effect of polyvinyl alcohol (PVA) fibres on slant shear tests with different slants of the repair interface, they indicated that the incorporation of PVA fibres in repair materials improves their interface properties by minimizing shrinkage and micro-cracks propagation [24,25].

Many researchers studied the possible use of marble powder to replace cement, others investigated the incorporation of polypropylene fibres however, there are a lack of data and few studies have been conducted to evaluate the synergic impact of marble powder and PPF on repair applications regarding rheological behaviour, thermal conductivity, mercury intrusion porosity MIP and adhesion bond strength in hot-dry climate. The aim of this project is to contribute to a better understanding the effect of incorporating marble powder in cementitious repair mortar reinforced with polypropylene fibres and durability of repair system in a hot-dry climate.

For this purpose, a bibliographic study includes chapters 1 to 3 is presented in this thesis. The first chapter provides an overview of the main pathologies that threaten the durability, strength, and even the stability of structures, potentially leading to their failure. A detailed overview of the key stages of a diagnosis, as well as the experimental methods and techniques for concrete

General introduction

rehabilitation according to the specifications of the EN 1504 standard, are presented in this chapter.

The second chapter aims to provide a detailed overview on self-compacting mortars (SCM) and fibre-reinforced self-compacting mortars (FRSCM), the type of filler used as a cement substitute, as well as their potential applications. Particular attention will be given in this chapter to the various methods of characterizing these mortars.

The third chapter addresses recent studies concerning the effect of marble powder as cement substitute on the rheology, mechanical properties, modulus of elasticity, shrinkage, water absorption... etc. as well as the effect of hot climate on the properties of concrete and mortar was elaborated. Moreover, parameters that could influence the compatibility between repair mortar and old concrete.

The materials and experimental methods employed in this study are presented in the fourth chapter, based on the specifications and guidelines of EFNARC and the performance requirements for repair mortars outlined in EN 1504-3.

As for the final part, which includes the fifth chapter, it is entirely devoted to the presentation, analysis, and synthesis of the results produced as part of the experimental work (Chapter V). Finally, in the conclusion, we will provide an overview of the achievements of this work, and some perspectives will be presented.

Chapter I

Pathologies of Reinforced Concrete Structures and Repair Techniques

I.1 Introduction

This chapter is initially dedicated to describing the main causes of the deterioration of reinforced concrete structures. Material degradation resulting from the presence of aggressive agents and mechanical degradation, on the other hand, arise from excessive stresses applied during service. Then, we will briefly present the various repair techniques commonly used over the years, as well as those developed in recent decades using composite materials.

Improperly performed and poorly executed repairs can result in financial costs that significantly exceed the initial repair expenses. The industry employs a variety of repair techniques and methods, making it crucial to understand the mechanisms and failure modes associated with these different concrete repair approaches [26].

I.2 Deterioration of Reinforced Concrete Structures

Reinforced concrete structures are exposed to aggressive environments that accelerate their deterioration. The durability of reinforced concrete structures depends on their behaviour in response to the climatic and environmental conditions present in the areas where they are built, as shown in Figure I. 1.

These structures are often subjected to various physico-chemical aggressions, which they must withstand to adequately perform all the functions for which they were designed during their service life. When they fail to resist these aggressions, disorders occur, the most common of which is the corrosion of reinforcements. This accelerates the deterioration of these structures, leading to significant financial costs for municipalities.

These disorders are generally caused by design flaws, poor implementation, or accidental factors; they compromise the durability, strength, and stability of the structures and may lead to their degradation and eventual ruin. Consequently, these structures will require rehabilitation in the coming years to improve their performance, compensate for the loss of rigidity or strength caused by cracking, limit corrosion, and extend their service life.

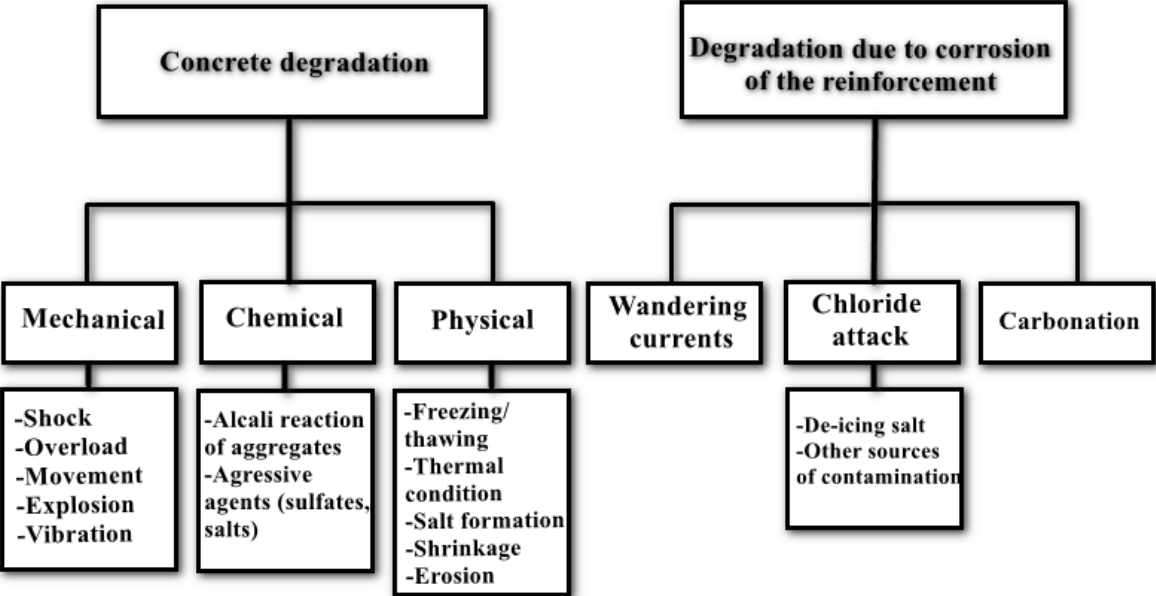


Figure I. 1. Different cause of concrete degradation [27]

I.2.1 Physical degradation

Concrete may be damaged by environmental factors such as fire, frost, shrinkage or abrasion.

I.2.1.1 Erosion, Abrasion, and Surface Cavitation of Concrete

Structures subject to erosion are primarily located in fluvial and maritime environments. They are exposed to the transport of solid particles induced by currents and the action of waves at each tide. The degradation of concrete through friction results in the creation of surface geometric defects, the appearance of spalling, and superficial chipping, which lead to the exposure of reinforcements and accelerate the risks of corrosion.

I.2.1.2 Freeze-Thaw Cycles

Depending on the porosity and permeability of the concrete, water can infiltrate and, under the action of freezing, expand, generate internal stresses, and create cracks. Freeze-thaw degradation of concrete (*Figure I. 2*) is exacerbated by thermal shocks caused by the heat released during the melting of ice, with an enthalpy of approximately 334 J/kg (80 cal/kg).

Frost attack on concrete may take the form of spalling of the surface, or it may cause random cracking. Damage is made more likely by the use of de-icing salts. Air-entrained concrete is far less susceptible to damage by frost than non-air-entrained concrete, so it should be used for repairs when further frost attack is likely. Pockets that can fill with water, or containing materials that can absorb water, are a source of trouble because the water in them will expand if it freezes (*Figure I. 3*), disrupting the surrounding concrete [28].



Figure I. 2 Alkali-aggregate reaction effects combined with freeze-thaw cycles [27]

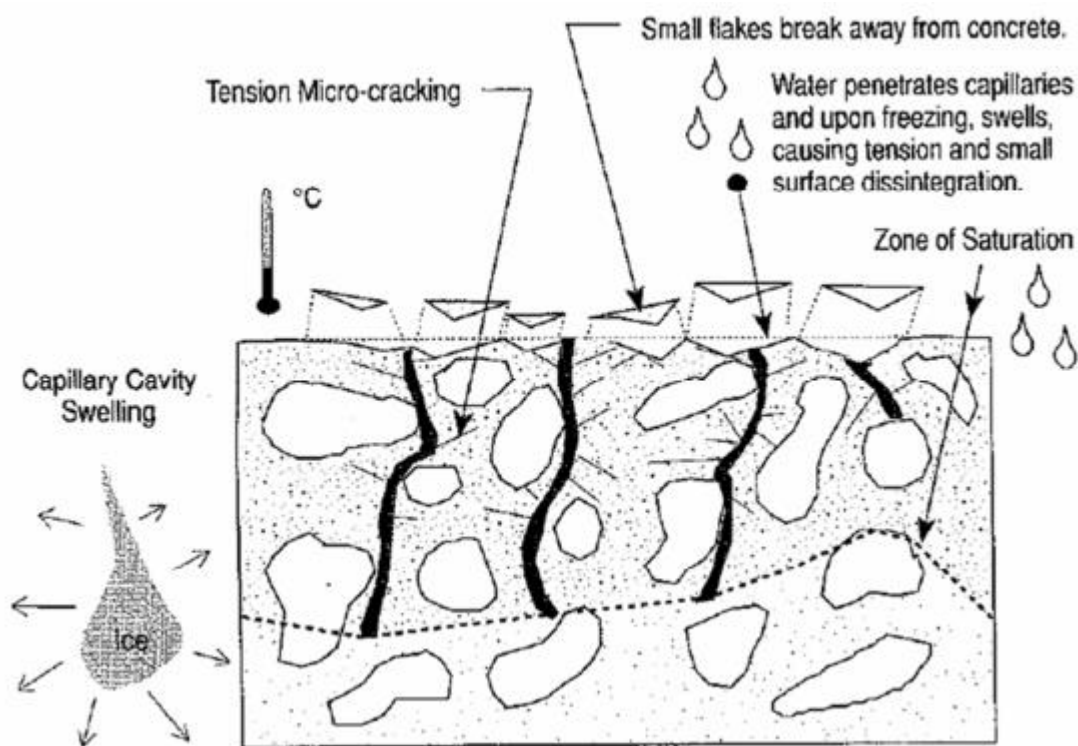


Figure I. 3 Freeze-thaw phenomenon [27]

1.2.1.3 Shrinkage

The evaporation of excess water from the concrete mix, added to ensure acceptable workability conditions, results in dimensional variations in the concrete [27].

Shrinkage causes 3 types of cracks:

- cracks that appear 1 to 2 hours after concreting. They are deep and may be open;
- cracks that appear after removing the formwork. They are found on horizontal surfaces and vertical facings;

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- Long-term cracks.

Shrinkage can hardly be stopped, but it can be limited by using certain materials such as superplasticizers (adjusting the W/C ratio) and fibres (increasing tensile strength).

I.2.2 Chemical degradation

Chemical degradation is usually the result of attack on the cement matrix. Portland cement is alkaline, so it will react with acids in the presence of moisture and, in consequence, the matrix may become weakened and its constituents may be leached out [28].

I.2.2.1 Sulphate attack

The sulphate reaction is caused by the action of sulphates (from external and/or internal sources) with lime and cement aluminates (Figure I. 4). The consequences of this reaction include the formation of a highly expansive product, commonly known as ettringite, causing serious damage accompanied by loss of mass and strength at the concrete surface.



Figure I. 4 Sulphate attack [27]

I.2.2.2 Alkali- aggregate reaction

Portland cement contains compounds of alkali metals (sodium and potassium), and their presence can lead to relatively high concentrations of hydroxyl (OH) ions in the pore fluid of the concrete. This highly alkaline solution can react with certain forms of silica, present in some aggregates, and produce an alkali-silicate gel. This gel will expand if it imbibes water and the expansive forces may be great enough to disrupt the concrete [28] (Figure I. 5).

Not all forms of silica are reactive, and three factors must be present simultaneously for damage to occur:

Chapter I: Pathologies of Reinforced Concrete Structures and Repair Techniques

- (1) A sufficiently high concentration of alkali metals
- (2) Reactive forms of silica
- (3) Moisture.

If any one of these is absent, damage will not occur. Alkalis in cement are usually shown in analyses as sodium and potassium oxides Na_2O and K_2O [28].



Figure I. 5 Alkali-aggregate reaction [27]

I.2.3 Mechanical degradation

The mechanical stresses induced by the load applied to structures can lead, in the long term, to irreversible damage. Mechanical degradation is characterized by cracks. However, concrete is typically already cracked under service conditions. "Normal" cracks are associated with the functioning of reinforced concrete and are not detrimental.

These so-called normal cracks are:

- Cracks caused by bending, with openings of 0.2 to 0.3 mm.
- More generally, cracks with openings up to 0.4 mm.

Other cracks are referred to as "abnormal" cracks and may result from:

- Poor construction practices (improper placement of reinforcement, inadequate concrete composition).
- Temperature effects.
- Loads and forces acting on the structure.

These abnormal cracks result in:

- A reduction in the rigidity of the load-bearing structure and the formation of undesired hinges, causing changes in force distribution and the static system.
- Increased penetration of corrosion agents (moisture, CO_2 , chlorides, etc.). [27]

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1.2.3.1 Design or Execution Errors

This type of defect can result from errors occurring either during the design phase of the structure or during its execution. In the first case, the causes of cracking and degradation are generally due to severe errors in verifying the stability of the structure and its resistance conditions, or more simply, to the consideration of incorrect assumptions regarding loading conditions, environmental factors, or the functioning of the structure.

Such errors typically lead to poor dimensioning of sections and unsatisfactory placement of reinforcements, which result in unacceptable crack formations or structural failures. Many bridges exhibit defects caused by improper design concerning bending and shear resistance [29].

Among the particularly poorly evaluated conditions are:

- The effect of temperature gradients on a structure.
- Incorrect estimation of prestressing forces due to errors in trajectory design and inaccurate data regarding cable relaxation and their interaction with the structure (friction).
- Improper dimensioning of frames and their spacing to resist shear forces in reinforced concrete or errors in estimating corrections for the Résal effect (refer to BPEL regulations) in prestressed bridges.

These issues often lead to structural cracking that necessitates immediate rehabilitation.

Finally, an inadequate assessment of cyclic loading conditions and the fatigue behaviour laws of materials can undermine the validity of calculations and the design for the anticipated lifespan of the structure.

Notably, the impact of poorly identified behaviour laws for passive or active reinforcements and concrete under combined actions (fatigue, corrosion) can affect the stability of structures and lead to the formation of damaged zones.

Execution errors requiring intervention on the structure include:

- Formwork imperfections.
- Defects in concrete pouring.
- Reinforcement inconsistencies.
- Unsatisfactory conditions during the removal of formwork. [30]

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1.2.3.2 Modification of Operating or Usage Conditions of Structures

Changes in loading conditions are often caused either by modifications to regulatory axle loads or by changes in the frequency of applied stresses.

In some cases, it is also necessary to account for extreme stresses (climatic or accidental) that were underestimated during the construction of the structure. This is particularly true for the retrofitting of bridges or buildings to comply with seismic loads or the reinforcement of certain structural elements (such as bridge piers or side beams) to withstand accidental stresses, such as vehicle impacts [31].

The emergence of damage from these various causes may sometimes require repairs to extend the lifespan of structures and ensure greater reliability. [27]

1.2.3.3 Temperature Effects

Fires can cause severe damage to concrete in civil engineering structures. During a fire or thermal shock, the interstitial water within the concrete turns into steam. If this steam cannot escape quickly enough, the vapor pressure exceeds the tensile strength of the concrete, causing a kind of spalling. This spalling progresses toward the core of the material as long as the fire remains uncontrolled and the concrete temperature remains high.

The more the concrete exhibits reduced permeability and porosity, the greater the extent of the damage [27].

1.2.3.4 Fatigue Loading

Fatigue is a phenomenon where cracks that develop in concrete or reinforcement under repeated loading led to the spalling of the concrete cover and the failure of the steel. Fatigue failure can occur if excessive loads are repeatedly applied.

An example of this is the sagging of a reinforced concrete slab caused by the repetitive loading of vehicle wheels on a bridge [27].

1.2.4 Corrosion of Steel Reinforcements

The corrosion of reinforcements is arguably the most widespread deterioration phenomenon in reinforced concrete. For this phenomenon to develop, it suffices for structural elements to be exposed to moisture. The concrete cover provides a physical barrier and chemical protection due to its alkalinity [32,33]. Corrosion progresses more rapidly when the concrete cover is thin and the structure is exposed to chlorides. On the surface of steel embedded in hydrated cement

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paste, a thin layer of adherent products forms, which protects the steel. This protection is effective at high pH levels ($\text{pH} > 13.0$).

The breakdown of the protective microfilm occurs due to the presence of chloride ions or carbonation of the concrete. Thus, the cover provides physical protection to the reinforcements when it has a certain level of impermeability.

In general, the corrosion mechanism can be divided into two distinct phases. The first is the initiation of corrosion (chlorides penetrate the concrete, and the concentration of this agent exceeds a critical threshold, or the carbonation depth exceeds the thickness of the cover). The second phase involves the growth of corrosion on the reinforcements.



Figure I. 6 Corrosion of reinforcement [27]

Probably the most frequent cause of damage to reinforced concrete structures is corrosion of reinforcement, and this is usually the result of carbonation of the concrete or the presence of chlorides (Figure I. 6). Normal concrete is alkaline ($\text{pH} 12.5$ or more) and a passivating layer of oxide quickly forms on the surface of steel embedded in it. If the alkalinity falls below about $\text{pH} 10$ the passivating layer is destroyed and, in the presence of oxygen and moisture, the steel will corrode. If chlorides are present in the concrete, passivation is lost at a higher pH value, depending on the chloride ion concentration [28].

1.2.4.1 Carbonatation

Carbonation occurs as a result of penetration of carbon dioxide from the atmosphere (Figure I. 7). In the presence of moisture this forms carbonic acid which neutralizes the alkalinity of the cement matrix. The depth of penetration of carbonation into concrete is proportional to the

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square root of time so that, even if the surface layer of concrete carbonates quickly, the rate of penetration will slow down with increasing depth (5). The penetration rate depends also on the cement content and permeability of the concrete, so that an adequate depth of well-compacted cover of good quality concrete will protect the reinforcement for many years [28].



Figure I. 7 Carbonation [27]

1.2.4.2 Chloride ions effect

Chloride-induced corrosion of reinforcement occurs principally in older structures or in those that are exposed to chloride containing materials such as sea water or de-icing salts (*Figure I. 8*). It is not possible to specify a limiting chloride content below which corrosion will not occur because a number of factors are involved [28].



Figure I. 8 Effect of chloride ions [27]

I.3 Effect of Hot Climate on Concrete Durability

Hot climate is characterized by high temperatures, low relative humidity, high wind speeds, and intense solar radiation. These factors, especially when combined, tend to impair the quality of fresh or hardened concrete. Where one or more of these factors prevail, the temperature of the concrete and the rate of water evaporation increase rapidly, thermal movements and stresses become significant, and chemical reactions such as cement hydration and chemical attack are accelerated [34].

Daily temperatures in Algeria often reach 35°C on the coasts and even higher in the centre and the south during June, July, and August, the hottest months of the year. The average maximum temperature in summer can exceed 45°C, while the average minimum ranges from 35°C to 40°C in summer.

High temperatures are always the main causes of concrete degradation. They lead to more severe issues in dry climates and promote the rapid evaporation of mixing water, resulting in significant shrinkage. This evaporation is particularly concerning when it affects the water needed for hydration.

Air always tends to reach its saturation point. The lower the hygrometric degree of the air, the greater its absorption capacity. In other words, the amount of water the air can absorb to reach its saturation point is significant. This leads to a higher rate of water evaporation [34].

For example, in southern Algeria, relative humidity varies from a maximum average of 30% to 70% to a minimum average of 10% to 30% throughout the year. In the north, relative humidity averages above 70% and can reach up to 95%, whereas in the high plateaus, it can drop to as low as 35%.

Low relative humidity leads to rapid evaporation of the mixing water in concrete, which in turn accelerates the hardening of the concrete.

High solar radiation can cause heating of materials and equipment used in concrete production to heat up, resulting in a high initial temperature of the mix [34].

The skies in the southern regions of Algeria are generally clear. Average daily hours of sunshine are 7 to 8 hours in winter and 12 to 15 hours in summer. Solar radiation can also accelerate the evaporation of water from the surface of the concrete as it hardens, leading to a risk of plastic shrinkage cracking and reduced long-term durability.

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An increase in wind speed will lead to an increase in the rate of water evaporation. It is estimated that water evaporation at wind speeds of 15 and 40 km/h is 4 and 9 times higher, respectively, than in calm air conditions [35].

Salts carried by the wind can attack the exposed surfaces of hardened concrete and settle on aggregates, leading to a high amount of salts inside the concrete unless precautions are taken.

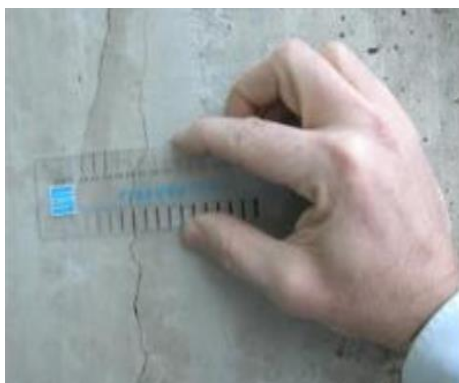
Winds in southern Algeria are generally stronger and more persistent than in the rest of the country [34].

I.4 The main steps of a diagnosis

The success or failure of the repair largely depends on the quality of the diagnosis.

- Site inspection
- In situ testing
- Sampling
- Laboratory analysis
- Prospective studies

The Figure I. 9 shows the main steps to follow when diagnosing a structure.



Crack test [36]



Electronic crack width meter [36]



Sclerometric measurements with recorder [37]



Electrode wheel for estimating corrosion [38]

Figure I. 9 Main devices used in the diagnosis of reinforced concrete structures

I.5 Main steps for repairing reinforced concrete structures

I.5.1 Removal of deteriorated concrete

It is imperative at this stage to remove all non-adherent concrete parts from the substrate. The process involves identifying, by listening (with the ear), and tapping the concrete surface to locate areas that "sound hollow" and are therefore affected by internal cracks caused by the pressure of oxidized reinforcements [39]. Furthermore, when the carbonated concrete zone extends to the reinforcements, it is necessary to completely remove the concrete surrounding the reinforcements until healthy concrete is exposed. Subsequently, the residual diameter of the corroded reinforcements must be measured in accordance with the diagnostic recommendations.

I.5.2 Surface Cleaning

Surface cleaning is a necessary step to remove all dust, debris, and even oils to achieve the desired adhesion between the repair material and the healthy concrete. The cleaning method varies depending on the surface preparation techniques [40]. Indeed, the cleaning method must be compatible with the repair product. There are dry methods (brushing and vacuuming, air-blasting with dry, oil-free air) and wet methods.

I.5.3 Surface Humidification

Before applying a repair material based on a hydraulic binder to the concrete substrate, the surface must be pre-moistened a few hours before the repair. This ensures good adhesion and prevents the desiccation effect (plastic shrinkage) of the new material.

I.5.4 Treatment or Replacement of Existing Reinforcements

During a concrete repair operation, care must be taken not to pour the repair material over reinforcements showing signs of corrosion, dirt, oils, or any suspicious substances. For slightly corroded reinforcements, cleaning should be carried out using brushing (manual and/or mechanical) or high-pressure sandblasting, followed by the application of an anti-corrosion (passivating) coating on the reinforcements without spilling onto the concrete.

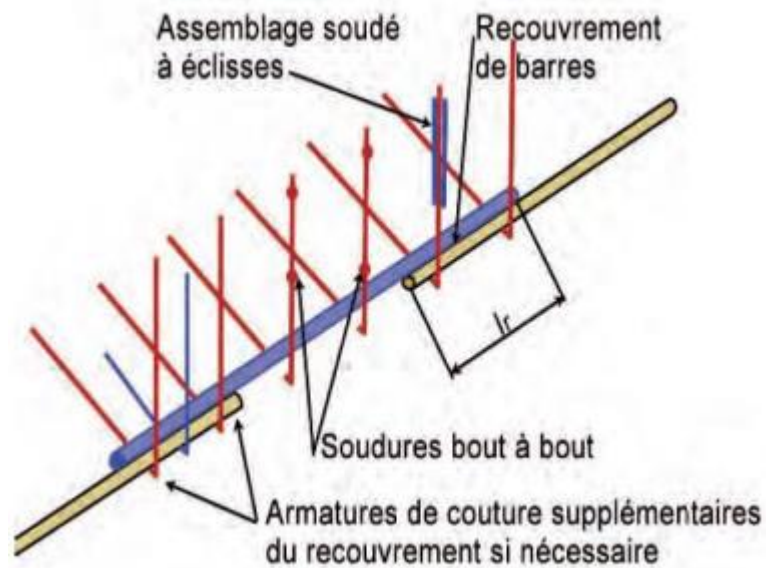


Figure I. 10 Principle of Replacing Damaged Reinforcement Extracted from the STRRES guidelines [41].

However, heavily corroded reinforcements must be replaced with new reinforcements to restore the load-bearing capacity of the element (Figure I. 10).

I.5.5 Application of the Repair Material

This final step involves restoring the initial shape of the concrete element by applying a repair material. It is important to note that the choice of repair material results from a thorough on-site diagnosis. Consequently, the chosen material must be adherent and demonstrate better resistance to future deterioration agents compared to the old concrete.

It is also worth mentioning that the use of bonding agents, such as mortar, mortar with latex, or epoxy resin, is sometimes recommended. Wells [42] observed that using such agents can significantly improve the adhesion of the repair, particularly when the surface is insufficiently treated (not roughened). However, Silfwerbrand et Paulson [40] disagree to some extent. They argue that applying a bonding agent creates two contact interfaces and, consequently, two potential planes of delamination between the repair material and its substrate.

I.6 Repair materials

Several types of repair materials are now available, which can be classified into three categories: cementitious materials, polymer-modified cementitious materials, and resinous materials [43,44]. For a durable repair, an in-depth understanding of the mechanical and physical characteristics of the available products and the existing substrate is necessary before

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selecting the appropriate repair material. Table I. 1 gives the properties of typical concrete repair materials [45].

Cementitious Materials: In addition to their cost advantage, cement-based repair materials have mechanical properties that are essentially similar to the concrete substrate. Therefore, the possibility of using them should be considered before deciding to use any repair material. Cementitious and resinous materials are widely used today, with cementitious materials being effective and economical in most cases [46]. They are made of cement and can be impregnated with a polymer, silica fume, fly ash, or other materials. Some of the drawbacks of repair mortars and concrete include high shrinkage and a tendency to crack. Additionally, in cold temperate climates, the rate of strength gain is too slow.

Polymer Materials: Since the early 1950s, it has been known that the addition of polymers to certain cement mortars helps solve the problems associated with using cement-based mortars as concrete repair materials. There are different types of polymers used as modifiers for cementitious materials, such as polyvinyl acetates and styrene-butadiene. Most of them are specifically manufactured as additives [46].

The polymer serves to reduce water content, producing a mortar with good workability and low shrinkage at lower water/cement (W/C) ratios. They reduce the permeability of the repair mortar to water, carbon dioxide, and increase its resistance to certain chemicals. They also improve the adhesion between the repair mortar and the old concrete. Additionally, they increase the tensile and flexural strength of the mortar. Polymer-modified cementitious materials are made by partially replacing Portland cement or compound cement with polymers, at a rate of 10-20% by mass. The addition of polymers can improve the mechanical properties, permeability, and durability of repair materials [45].

Resinous Materials: The first practical application of epoxy resin took place in Germany and Switzerland in the 1930s. There are several advantages to using epoxy resins in concrete. The properties of epoxy resins that make them desirable for use in concrete are [46]:

- **Adhesion:** Epoxies have excellent adhesion to concrete.
- **High resistance to acid and alkali attacks.**
- **Rapid curing, low shrinkage, and high impermeability to water.**

A study conducted by [47] evaluated the behaviour of epoxy resin for use in repairing damaged structures while maintaining adhesion and durability properties. These authors concluded that

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the use of epoxy-modified repair mortars, along with an epoxy primer layer, provides better durability and very high adhesion strength due to the homogeneity of the microstructure.

Table I. 1 Properties of Typical Concrete Repair Materials [45].

Type of Repair Material	Polymer-based repair mortar	Polymer-modified Cement repair mortar	Cementitious repair mortar
Compressive strength (MPa)	50-100	30-60	20-50
Flexural strength (MPa)	10-15	5-10	2-5
Elasticity modulus (GPa)	10-20	15-25	20-30
Coefficient of Thermal Expansion (°C)	25-30. 10^{-6}	10-20. 10^{-6}	10- 10^{-6}
Maximum Service Temperature (°C)	40-80	100-300	>300

I.7 Concrete repair techniques using cementitious mortar

Each technique must be chosen based on the type of damage, the repair material properties, and the expected service conditions of the repaired structure. Proper preparation, application, and curing are essential for durable and effective repairs.

I.7.1 Hand-Applied Mortar

Concrete repair using mortar is a more economical method in cases of minor damage. The mortar is traditionally applied using a trowel, ensuring it penetrates the prepared substrate and is compacted to avoid defects such as air bubbles or voids, thereby achieving good adhesion and protecting the reinforcements against corrosion. The mortar can be applied in multiple layers. However, it is essential to wait until the initial layers are sufficiently rigid before applying a new layer to prevent sagging of the repair material.

I.7.2 Mortar filled into Formwork

This method is generally used for repairing load-bearing elements such as columns, beams, and slabs, which are often difficult to access and have a high density of reinforcements. The repair mortar used in this case has two main properties: fluidity and the ability to encase the reinforcements. The mortar is applied by pouring it into a space defined by the surface of the concrete to be repaired and a watertight formwork. It must be free of any signs of segregation or bleeding. To ensure a continuous flow, the mortar can be delivered using a pump if necessary.

I.7.3 Sprayed Mortar

This technique is widely used both for strengthening inadequate or failing structures and for repairing damaged structures. It allows the application of large volumes of mortar layers (with a maximum aggregate size ≤ 5 mm) designed to conform to the damaged structure and increase the cover thickness over reinforcements on extensive surfaces, without the need for formwork. This method is also suitable for sites that are difficult to access using conventional pouring or manual application techniques. There are two spraying methods, depending on the timing of water introduction into the machine.

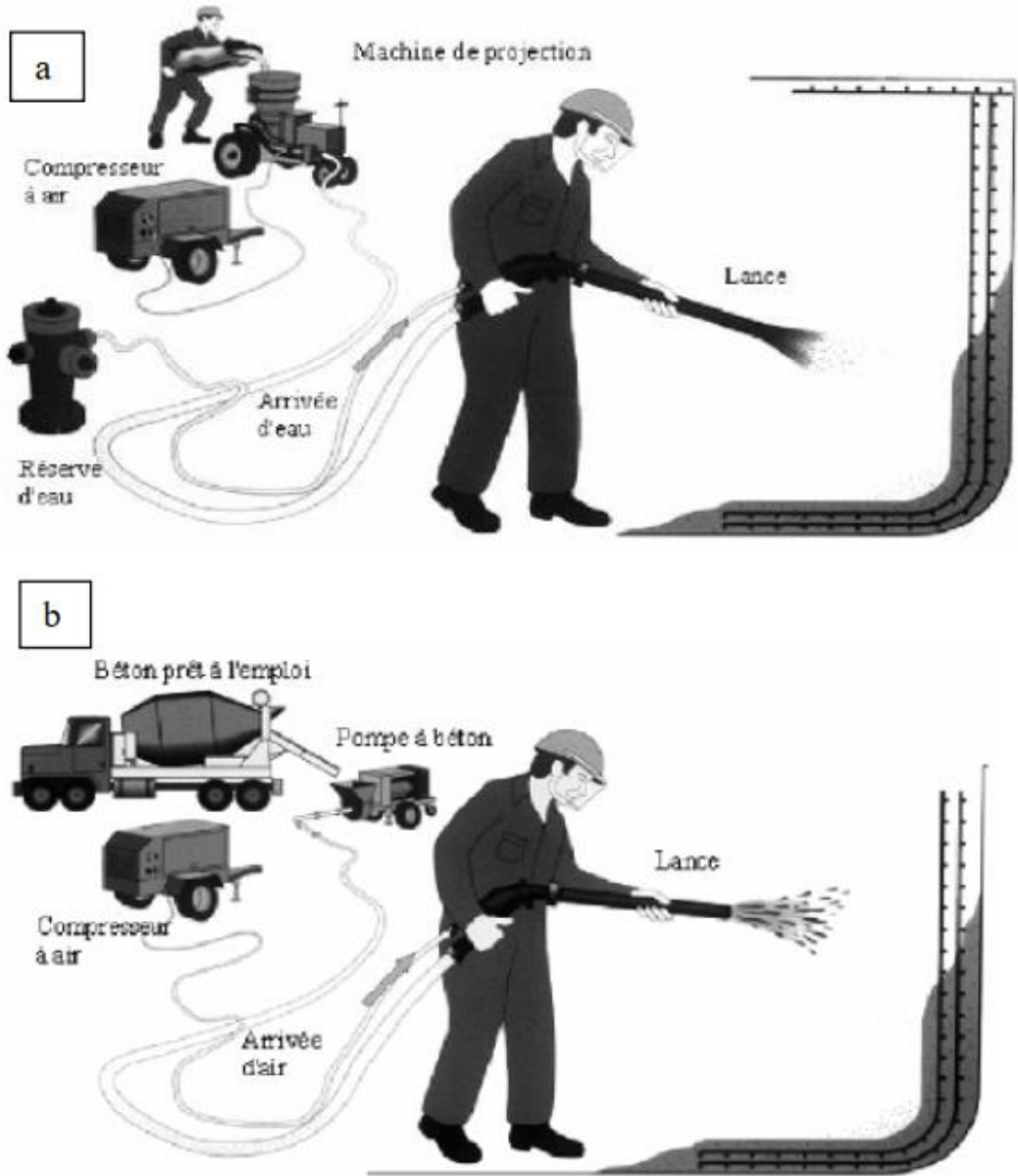


Figure I. 11 Strengthening Structures with Sprayed Mortar: (a) Dry Spraying Method, (b) wet Spraying Method.

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- Dry-mix spraying application (Figure I. 11.a): Water is introduced at the last moment at the nozzle level. The machine can spray over significant distances. This technique is used for structural repairs because it ensures good adhesion as well as high mechanical strength (Figure I. 12).
- Wet-mix spraying application (Figure I. 11.b): Water is mixed with the mortar during the mixing process. The machine sprays over very short distances with a velocity less than 1m/s. This technique is used in underground works due to its high compressive strength. It produces less rebound and therefore less dust than the dry-mix method.

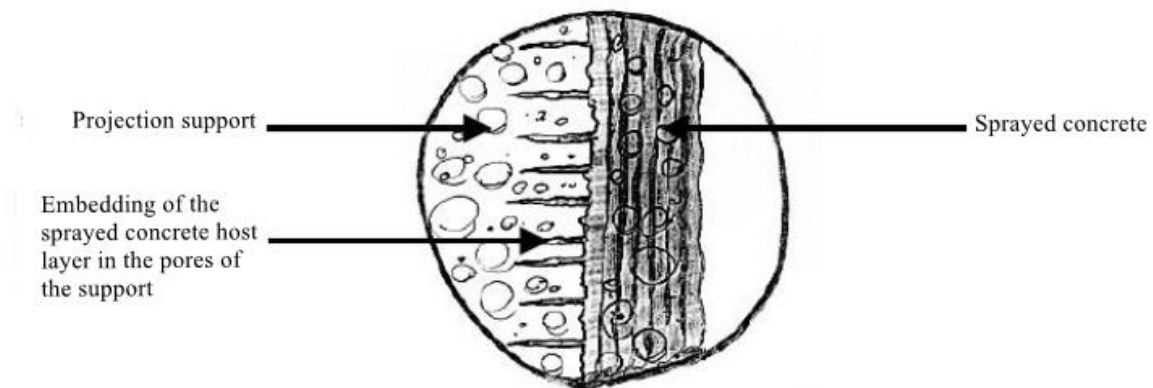


Figure I. 12 Mechanical adhesion due to the embedding of fine particles into the pores of the substrate [48]

I.8 Classification of repair mortars according to the EN 1504 standard

There are four classes of requirements for repair mortars (Table I. 2). Indeed, the compressive strengths define these classes. There are two classes for non-structural repair mortars (R1 and R2) and two classes for structural repair mortars (R3 and R4).

The mortars in the first category are used on concrete surfaces to restore the geometric or aesthetic appearance of the structure. The mortars in the second category are applied to a concrete structure to replace defective concrete and restore the structure's integrity and durability. Currently, various types of concrete repair mortars are available on the market. The choice of material primarily depends on the thickness of the planned repair.

In the present study, only mortars based on hydraulic binders will be considered for concrete repair.

Chapter I: Pathologies of Reinforced Concrete Structures and Repair Techniques

Table I. 2 Performance requirements for structural and non-structural repair products.

Performance characteristics	Test method	Requirement (Table 3 according to EN 1504 part 3)			
		Structural		Non structural	
		Category R4	Category R3	Category R2	Category R1
Compressive strength	EN 12190	≥ 45 MPa	≥ 25 MPa	≥ 15 MPa	≥ 10 MPa
Chloride ion content	EN 1015-17	$\leq 0,05\%$		$\leq 0,05\%$	
Bond strength (pull-off test)	EN 1542	≥ 2 MPa	$\geq 1,5$ MPa	$\geq 0,8$ MPa	
Expansion/limited shrinkage	EN 12617-4	Bond strength after test			No requirement
		≥ 2 MPa	$\geq 1,5$ MPa	$\geq 0,8$ MPa	
Durability – carbonation resistance	EN 13295	$d_k \leq$ reference concrete		No requirement	
Durability – thermal compatibility freeze/thaw	EN 12617-4	Bond strength after 50 cycles			Visual inspection
		≥ 2 MPa	$\geq 1,5$ MPa	$\geq 0,8$ MPa	
Durability – thermal compatibility thunderstorm rain	EN 12617-4	Bond strength after 30 cycles			Visual inspection
		≥ 2 MPa	$\geq 1,5$ MPa	$\geq 0,8$ MPa	
Durability – thermal compatibility dry thermal cycles	EN 12617-4	Bond strength after 30 cycles			Visual inspection
		≥ 2 MPa	$\geq 1,5$ MPa	$\geq 0,8$ MPa	
Modulus of elasticity	EN 13412	≥ 20 GPa	≥ 15 GPa	No requirement	
Slip/skid resistance	EN 13036-4	Category I: ≥ 40 wet units Category II: ≥ 40 dry units Category III: ≥ 55 wet units		Category I: ≥ 40 wet units Category II: ≥ 40 dry units Category III: ≥ 55 wet units	
Capillary absorption	EN 13057	≤ 0.5 kg/m ² ·h ^{0.5}		≤ 0.5 kg/m ² ·h ^{0.5}	No requirement

I.9 Conclusion

In this chapter, the main causes for concrete degradation are illustrated, include chemical attacks, physical deterioration, mechanical damage, and environmental factors, all of which can compromise the durability and structural integrity of concrete. To address these issues, various types of repair mortars are available, such as polymer-modified mortars, fibre-reinforced mortars, and high-performance cementitious mortars, each tailored to specific degradation mechanisms and structural requirements.

Moreover, the literature review has shown that to achieve a successful repair, it is necessary to thoroughly understand the origin and causes of the defects, perform proper surface preparation, and apply a repair product that meets the compatibility requirements with the existing concrete.

Chapter II

Self-compacting repair mortars

II.1 Introduction

This literature review aims to present a state-of-the-art overview on fibre-reinforced self-compacting repair mortars. The first part focuses on defining self-compacting mortar, its composition, its characteristics, as well as its fields of application, while highlighting its advantages and disadvantages. The second part presents various types of mineral additions and their impact on concrete properties in both fresh and hardened states. A synthesis of studies on the effect of incorporating fibres on the rheological and mechanical properties of concrete is the focus of the third part. Particular attention will be given in this chapter to studies conducted on the addition of polypropylene fibres which are generally used for repair applications, insulation, and enhancing the physical performance of concrete as well as marble powder as cement replacement.

II.2 Self-compacting mortar

A new technological product that differs from conventional mortar due to its properties in the fresh state. Indeed, this type of mortar is capable of completely filling the formwork without the need for external energy (vibration), regardless of the level of confinement (dense reinforcement mesh or the presence of other obstacles). And it remains homogeneous during flow (absence of dynamic segregation) and once applied (absence of static segregation) (Figure II. 1). As a result, this mortar is particularly favoured for the rehabilitation and repair of degraded reinforced concrete structures [49], such as surfaces subjected to high abrasion rates (floors, slabs), beams with insufficient strength (in bending, tension, shear, and resistance to shear force), thin shells, walls, etc.

II.2.1 Composition of self-compacting mortar

Self-compacting mortar based on hydraulic binder must consist of a high volume of paste, a significant amount of fines, a high dosage of superplasticizer, and the possible use of a viscosity agent.

The use of a high volume of paste (cement + addition + effective water + entrained air) in the composition of self-compacting mortars helps to limit inter-granular interactions, which are a source of restrictions in terms of spreading and flow (effect of dispersing the aggregates from one another) (Figure II. 2).



Figure II. 1 Some applications of self-compacting repair mortars

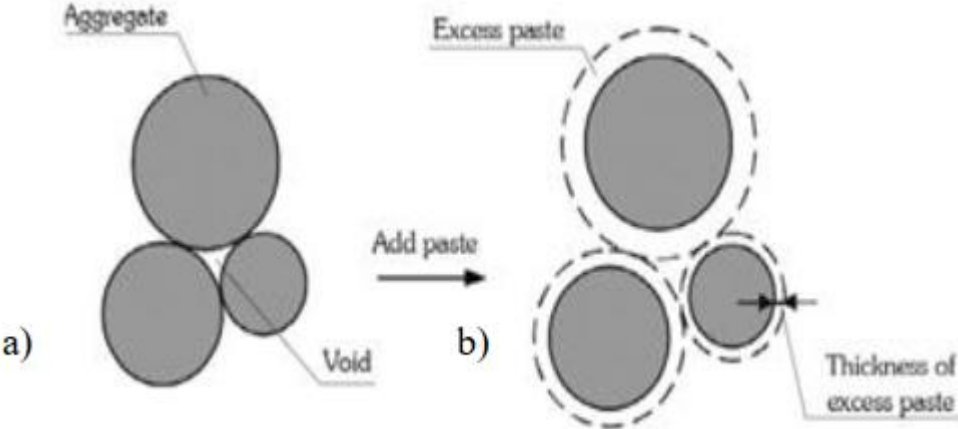


Figure II. 2 Notion of excess paste: the paste fills the porosity (a) and separates the aggregates (b)[50]

To ensure sufficient workability while limiting the risks of segregation and bleeding, self-compacting mortars (SCMs) contain higher amount of fines compared to ordinary mortars (OMs). However, to avoid issues of excessive temperature rise during hydration and to reduce

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their overall cost, the binder is often a binary compound [51], or even ternary [52], meaning Portland cement mixed with fly ash, slag, limestone filler, pozzolan, or silica fume.

The introduction of a relatively high dosage of superplasticizer in self-compacting mortars (SCMs) primarily allows for a reduction in water content while maintaining high workability. However, this addition must be close to the saturation dosage [53]; otherwise, it may increase the sensitivity of the SCM to variations in water content, leading to segregation and bleeding.

The possible use of a colloidal agent (cellulosic derivatives, polysaccharides, or colloidal suspensions) in self-compacting mortars (SCMs) serves to prevent bleeding and limit the risk of aggregate segregation by making the paste thicker. Schematically, the use of this product appears justified in SCMs with high W/B ratios, as the fines are not always sufficient to retain the water in the SCM. Conversely, it seems unnecessary in SCMs with low water-to-binder mass ratios [54].

II.2.2 Formulation of self-compacting mortar

The absence of coarse aggregates (gravel) in the composition of self-compacting mortar (SCM) or fibre-reinforced self-compacting mortar (FRSCM) mixtures has allowed the use of other characterization equipment to predict the desired flow properties of the mortar (plastic viscosity and yield stress). This is due to the difference in composition compared to self-compacting concrete (SCC) and/or fibre-reinforced self-compacting concrete (FRSCC). For this purpose, an optimization method for SCM and/or FRSCM, known as the Japanese method, was developed using small-scale equipment such as the mini V-funnel and the mini cone. It is worth noting that specifications and guidelines for self-compacting mortar, as well as other methods, have been developed; however, these methods are all based on the Japanese approach.

Mortar optimization method or Japanese method

This method was developed by Okamura and Ozawa, two researchers from Kochi University in Japan [55]. The main idea of the two researchers is based on achieving self-compacting concrete. This requires high deformability and appropriate viscosity of the paste or mortar so that the concrete can flow through narrow sections without separation between the aggregates and the paste. To obtain self-compacting concrete, the first step is to limit the volume of coarse aggregate to 50% of the volume of solids contained in the concrete, that is:

$$V_g = \frac{50}{100} V_{Glim} (1 - A) \quad (\text{Equation II. 1})$$

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Where

- V_g is the absolute volume of coarse aggregates per cubic meter of concrete;
- A is the air content (chosen based on freeze-thaw resistance).

Similarly, the volume of sand is set to 40% of the total volume of the mortar (Figure II. 3). The desired properties of the mortar (high deformability and adequate viscosity) are achieved through the use of a high powder content and an effective dosage of superplasticizer (SP)[56–58].

The fundamental steps of this method are summarized as follows:

- The air volume is assumed to be 1% in the absence of an air-entraining admixture, and between 4% to 7% otherwise;
- The quantity of coarse aggregates is set to 50% of their compactness;
- The sand content is limited to 40% of the mortar volume;
- The water-to-powder ratio (W/P) is assumed to be between 0.9 and 1.0 by volume, depending on the properties of the powder;
- The superplasticizer dosage and the final W/P ratio are adjusted in the mortars.

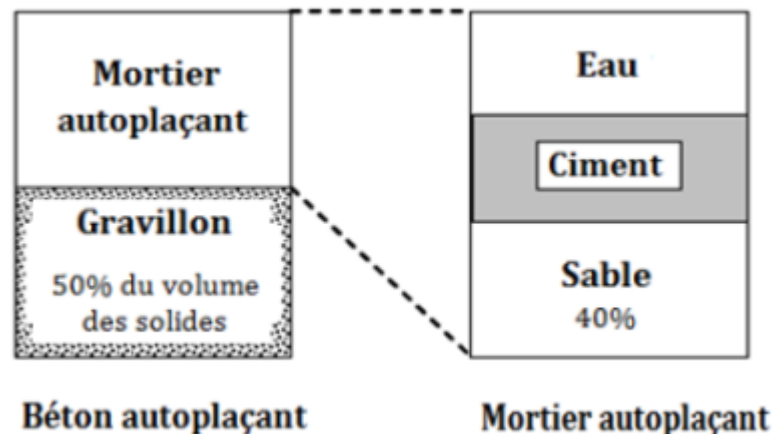


Figure II. 3 Proportions of coarse aggregates and sand in self-compacting concrete according to the general method [5].

The adjustment of the water-to-powder (W/P) ratio and the superplasticizer (SP) dosage involves conducting preliminary tests on the mortar: the mini-cone slump test and the mini-

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funnel flow test, as suggested by several researchers (Figure II. 4) [56,59]. Through these tests, the final spread diameter and flow time are measured, and the following two parameters are calculated:

- **Relative slump flow:**

$$\Gamma m = \frac{(d^2 - d_0^2)}{d_0^2} \quad (\text{Equation II. 2})$$

- **Relative flow velocity:**

$$Rm = \frac{10}{Tv} \quad (\text{Equation II. 3})$$

Where

- Γm is the relative slump flow,
- d (cm) is the spread diameter in cm,
- d_0 (cm) is the lower diameter of the mini-cone in cm,
- Rm is the relative flow velocity,
- Tv is the flow time in sec.

The relative spread helps identify the deformability of the mortar (the larger Γm , the more deformable the mortar), while the relative flow velocity represents the viscosity (the smaller Rm , the more viscous the mortar). Recommended values for relative slump flow and relative flow velocity are $\Gamma m = 5$ and $Rm = 1 \pm 0.1$, respectively, for producing self-compacting concrete with good fresh-state properties[55,60].

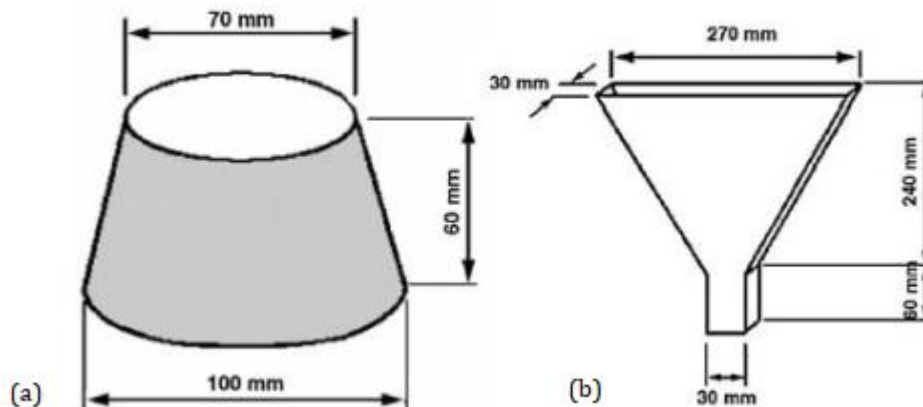


Figure II. 4 Fresh characterization of self-compacting mortar: (a) mini-cone slump test, (b) mini V-funnel flow test.

II.3 Specifications and guidelines for self-compacting mortar EFNARC

As part of this mortar mix design procedure, the sand particle size must be within the range of $0.125 \text{ mm} \leq \phi \leq 4 \text{ mm}$. The sand content is defined by its bulk density, and the optimal sand volume fraction in the mortar varies between 40% and 50%, depending on the paste properties. Additionally, the optimal water-to-powder ratio and the volumetric dosage of superplasticizer in the mortar must be determined.

To achieve the desired flow characteristics of the mortar, namely spread and flow time, EFNARC [61] recommends using the same apparatus proposed by Okamura and Ouchi.

Accordingly, the spread and flow time of the mortar are measured at different water-to-powder ratios and various superplasticizer dosages. The target values are a spread between 24 and 26 cm and a V-Funnel flow time between 7 and 11 seconds. According to EFNARC specifications, if the target flow time is below 7 seconds, the water-to-powder ratio should be reduced. Conversely, if the flow time exceeds 11 seconds, the water-to-powder ratio should be increased.

It should be noted that if these criteria cannot be met, testing with a different superplasticizer is the preferred alternative. Otherwise, a complete change of cement (with a different additive) may be necessary.

II.4 Principal constituents of self-compacting mortars

We can classify the components used in the production of self-compacting concrete (SCC), based on their function, into three categories: basic materials (cement, aggregates, and mixing water), mineral additives, and chemical admixtures (superplasticizers and/or colloidal agents).

II.4.1 Cement

All cements that comply with the EN 197-1 standard are suitable for the formulation of mortars and even self-compacting concretes. In fact, the selection of the type of cement depends on certain desired properties [62], such as strength, durability, etc. From a rheological perspective, the cement properties that influence the flow of mortar paste are primarily the mineralogical composition, particle size distribution, and fineness [63,64].

II.4.2 Sand

The sand used in all formulations of self-compacting mortar (SCM) is often the same as that used for ordinary mortars or concrete. It can come from natural sources (river, mountain) and/or artificial sources (quarry). It should be noted that the fine particles in the sand, with a diameter

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smaller than 0.125 mm, are considered as powder. Indeed, these powders are beneficial for the rheology of self-compacting mortars [54].

II.4.3 Mineral additions

Cementitious additives are materials with a very fine particle size that are often incorporated into cement and sometimes into concrete. These additives are used either to improve the characteristics of the concrete or to provide it with specific properties. Additives are less expensive than Portland cement and make it possible to produce a more economical blended cement.

Self-compacting mortars contain significantly larger amounts of mineral additives (fines) compared to ordinary mortars. These additives have been the subject of extensive research [15,65–68]. Indeed, these additives are small-sized particles (particles <125 μm), which can be either chemically inert (type 1) or active (pozzolanic) (type 2).

II.4.3.1 Additions type I

Type I additives are fine particles that can be inert, organic, natural, or synthetic. They tend to compensate for the deficiency of fine particles by filling part of the voids in the granular skeleton, thereby improving the physical properties of mortars and/or concrete (workability, water retention, etc.). Among these additives, we distinguish limestone, dust, and fillers.

Limestone fillers: it is mineral fines obtained by grinding limestone rocks, often of organic origin (limestone with foraminifera such as chalk, shell limestone) but also of chemical origin (calcite, pisolitic, lithographic) [69]. They are characterized by a chemical composition predominantly consisting of calcium carbonate (CaCO_3) with a content exceeding 75%. The use of these fillers can enhance several properties of the cement matrix through physical and/or chemical effects [70]. From a physical perspective, limestone fillers can replace unhydrated clinker particles [71] or even fill the voids between larger particles, such as cement and sand, due to the filler effect (Figure II. 5).

Chemically, the addition of limestone to Portland cement further accelerates the hydration of C_3S in the early stages, especially when the particles are fine and the CaCO_3 content is significant (up to 15–20% by mass) [72,73].

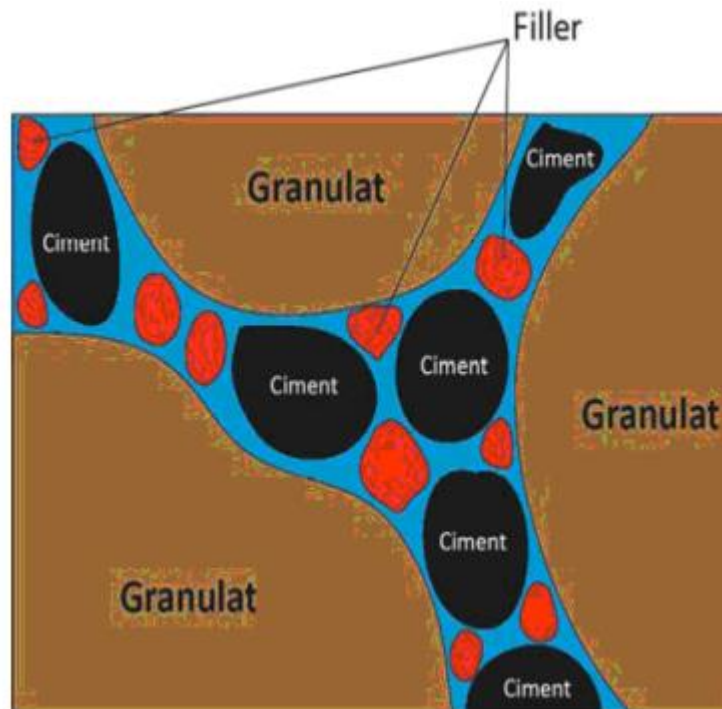


Figure II. 5 Filler effect [74]

According to Cyr et al. [75], limestone reacts with C_3A and C_4AF to form carboaluminates. Indeed, the formation of hydrated calcium carboaluminate at early ages is linked to a high concentration of $CaCO_3$ in the cement, resulting in an increase in mechanical strength starting from 2 days, although this becomes negligible at 28 days [76,77].

Marble powder (MP) as waste material, produced during the cutting process of marble rocks, should not be ignored due to its huge quantity and the serious environmental problems encountered [78,79]. It has a negative influence on both people's social and industrial activities. Marble is a metamorphic stone formed by the transformation of limestone (calcite- $CaCO_3$). 30%- 40% of processed marble in factories is a production waste [13]. Its utilization in the industry yields substantial returns in terms of economic and environmental performance [80]. MP could be incorporated in concrete, cement or synthetic resins [81]. The effect of MP on concrete properties is more detailed in chapter III.

II.4.3.2 Additions type II (hydraulic and/or pozzolanic reaction)

Additions of type II refer to active mineral additives (natural or artificial substances) that are finely ground and added to cement to enhance its strength and hydraulic properties. These additions include fly ash, silica fume, ground granulated blast furnace slag, metakaolin, natural pozzolan, nano-silica and perlite.

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Ground granulated blast furnace slag is a by-product of steel plants, mainly composed of silicates, calcium aluminosilicates, and other mineral substances. Once discharged from the furnace, it undergoes rapid cooling with a water jet, which gives it a glassy structure capable of reacting in the presence of calcium hydroxide released during cement hydration.

Boukendakdji, (2010) observed that the spread of concrete mixes made with PC superplasticizers (polycarboxylate-based) is higher compared to mixes with PNS superplasticizers (naphthalene sulfonate-based) (Figure II. 6). He also demonstrated that for both types of superplasticizers, the slope of the graph decreases when the slag content exceeds 15%, indicating that this percentage is optimal in terms of workability [82].

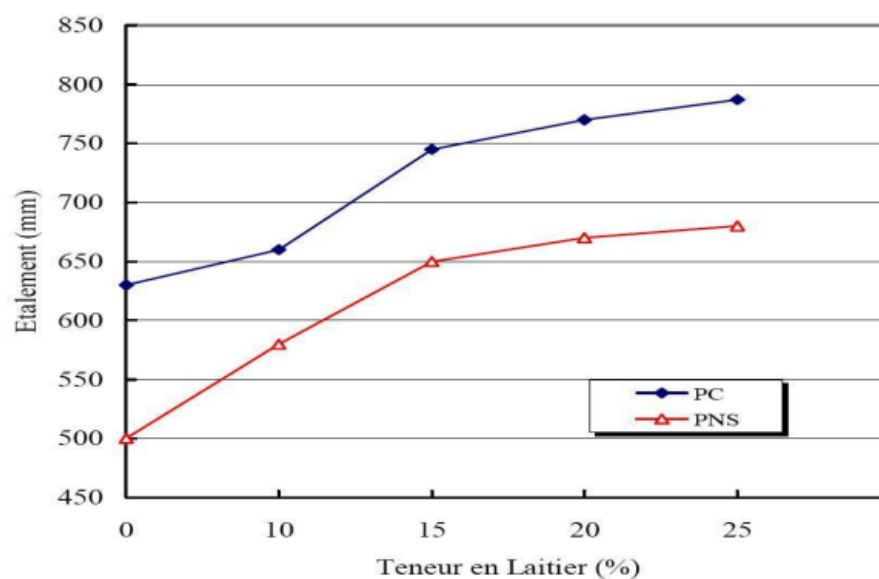


Figure II. 6 Slump flow of self-compacting concrete in function of slag content [82].

Li et Ding (2003) found that incorporating slag at a rate of 20 to 30% in mortar improves its workability [83]. Nécira et al. [84] achieved a spread of approximately 710 mm with 40% slag and around 630 mm with 10% slag in the mix (Figure II. 7).

Pozzolans are pyroclastic rocks formed from fragments of magma (pyroclastics) ejected into the atmosphere during volcanic eruptions and cooled during their airborne trajectory. The relatively high cooling rate, which has a quenching effect on the magma, explains why volcanic glass (an amorphous, non-crystalline material) is one of the major components of pozzolanic materials, along with other magmatic minerals (feldspars, pyroxene, olivine, iron oxide) and xenoliths.

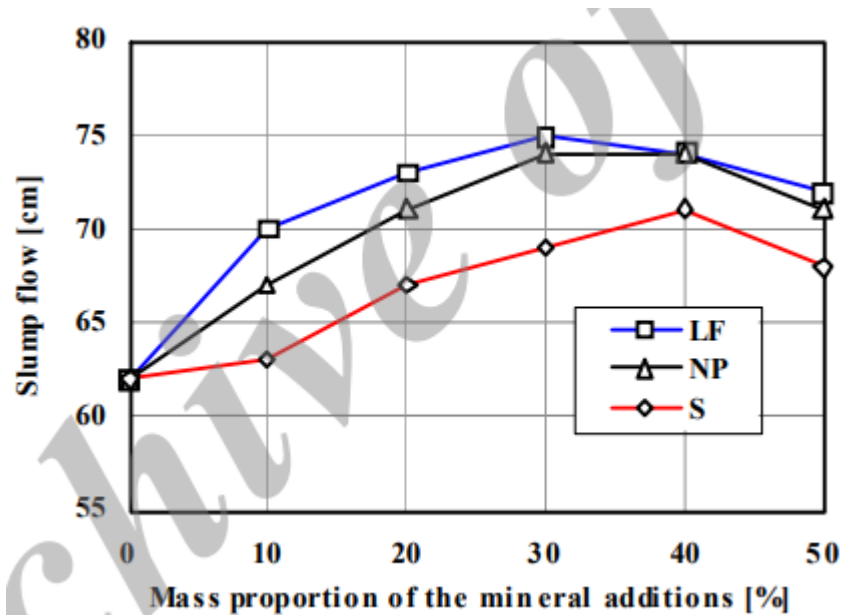


Figure II. 7 Effect of slag content on slump flow [84]

The constituents of natural pozzolans exhibit a coriaceous, vesicular texture. Based on their size, they are classified as ash (less than 2 mm), lapilli (2 to 64 mm), and blocks or bombs (greater than 64 mm). The colour of pozzolan typically ranges from black to red (brick red to dark brown), depending on the degree of iron oxidation, present respectively as magnetite or hematite. Natural pozzolans are primarily composed of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3).

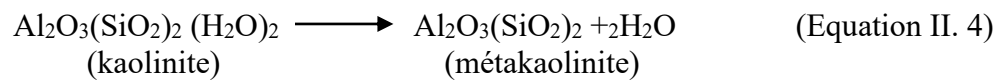
Silica fume (NF P 18-502) is an amorphous, finely divided powder. It contains approximately 90% silica in its chemical composition [59]. Silica fume is a by-product of the production of silicon and various types of ferrosilicon or zirconium alloys. The particles of silica fume are spherical in shape, with sizes ranging from 0.1 μm to 0.2 μm . The average size of these particles is 100 times smaller than that of cement particles. The standard distinguishes two classes of silica fume: A and B. Class A is rich in silica and very fine, due to its high fineness and significant reactivity with calcium hydroxide ($\text{Ca}(\text{OH})_2$). Silica fumes are used as substitutes in cement and/or concrete, with a content not exceeding 10%.

Fly ash is a very fine powder, mainly composed of glassy, spherical particles. It is produced by the combustion of solid mineral fuels (coal, lignite, etc.) in thermal power plants and possesses pozzolanic properties. The chemical composition of fly ash includes silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and lime (CaO), which largely depends on the origin of the fuel burned in the power plants. The total content of SiO_2 , Al_2O_3 , and Fe_2O_3 must not be less than 70%, and the reactive SiO_2 content must account for at least 25% of the mass (EN 450-1, 2005).

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Fly ash can reduce water demand and setting time [85]. They lower the heat of hydration of the binder [86]. The mechanical strength of binders containing fly ash is reduced at early ages but increases in the long term due to the pozzolanic reaction [87].

Metakaolin (MK) is a powdered, partially amorphous product resulting from the calcination of a clay, kaolinite, associated with various minerals (phyllosilicates, quartz, iron oxides) in variable proportions. The calcination of kaolinite into metakaolin (synthetic pozzolan) is carried out between 600°C and 800°C. This process causes the dehydration of kaolinite, with the overall reaction as follows:



Indeed, the calcination temperature mainly depends on the degree of purity of the kaolin [88]. The thermal treatment lasts approximately 5 hours in a rotary kiln, resulting in the transformation of the crystalline system. The use of 5% to 10% of metakaolin as cement substitution slightly improved the rheological behaviour and fresh properties of mortar. Increasing MK to 20% increased the yield stress, the viscosity, and flow time, but there was a decrease in slump. Moreover, mechanical strength was significantly enhanced in the presence of MK [89].

Perlite, according to ASTM C618, is an acidic, vitreous, and hydrated volcanic rock, light gray, greenish, or black in color, with a chemical composition similar to rhyolite (more than 72% SiO₂). Under rapid heating to an appropriate point (900 to 1100°C), perlite expands, creating countless pores, each of varying sizes on the micron scale. This process makes it lighter while providing significant advantages in terms of fire resistance and noise transmission, which contribute to its low density [90]. Ground perlite (perlite filler) can be considered a potential mineral admixture with high pozzolanic activity for concrete or mortar, due to its amorphous structure and high SiO₂ and Al₂O₃ content [91–93]. Erdem et al. [94] demonstrated that perlite powder exhibits pozzolanic reactivity when used as a replacement for Portland cement. Yu et al. [95] showed that when perlite is incorporated into mortar or concrete, it can mitigate the expansion caused by the alkali-silica reaction.

II.4.4 Superplasticizer

With a relatively high molecular weight (20,000 to 30,000) and a negative charge, synthetic polymers can adsorb onto the positive sites of cement grains through simple electrostatic attraction. Additionally, they can attach to the negative sites through complexation with calcium

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ions present in the solution. As a result, the cement grains tend to move apart from one another since they all carry the same charge and become coated with a very thin layer of water. Thus, the particles are dispersed, and the proportion of free water increases (*Figure II. 8*), (*Figure II. 9*).

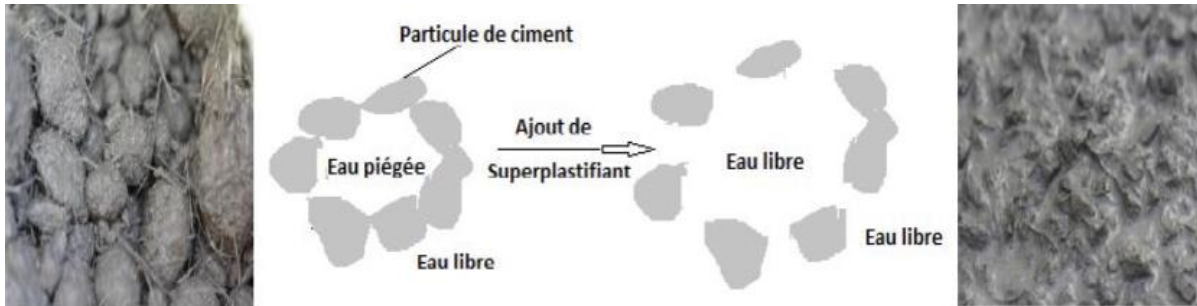


Figure II. 8 Dispersion of cement grains by adding the polymer [96]

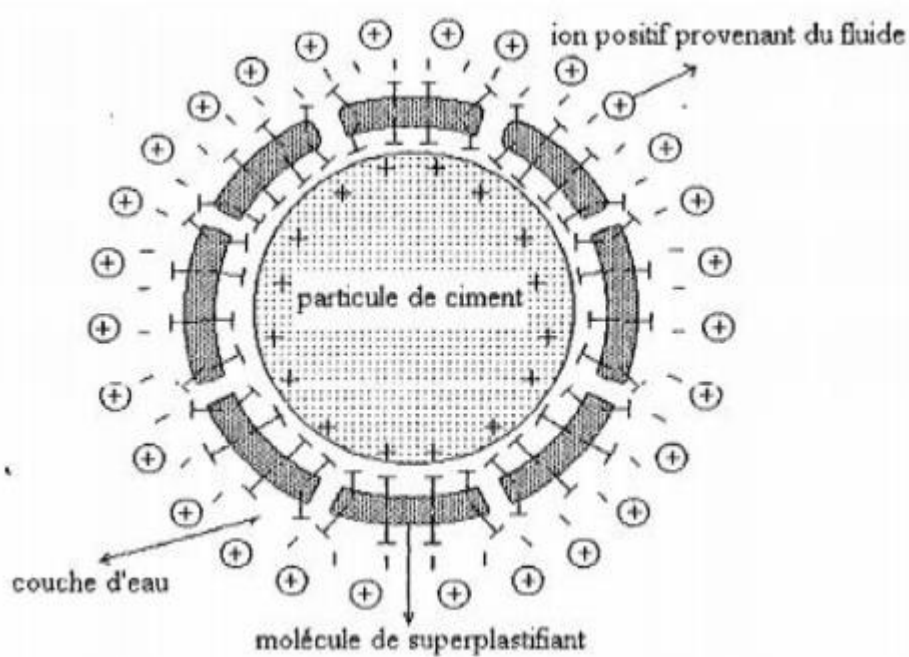


Figure II. 9 Mechanism of action of a superplasticizer molecule [54]

Given that self-compacting mortars must meet two conflicting characteristics, namely high strength achieved by reducing the water-to-binder ratio (W/B) and the desired workability, the use of superplasticizers makes it possible to reconcile the reduction in water content with the desired fluidity of SCC and/or SC mortars while maintaining the material's mechanical performance [97].

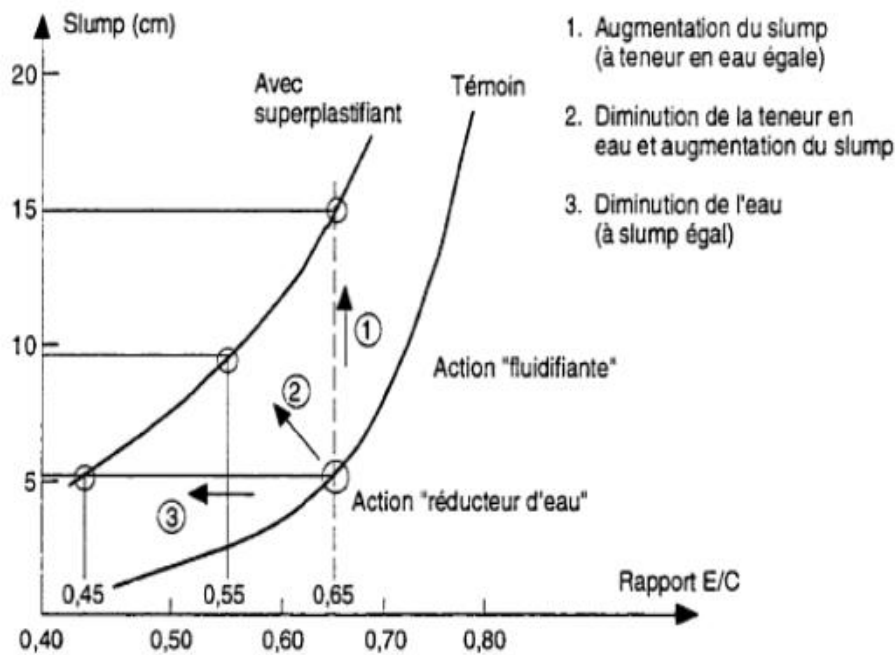


Figure II. 10 Effect of superplasticizer on rheological properties of SCC [97]

Indeed, the degree of compatibility of a cement/superplasticizer combination is assessed by the ability to maintain the spread of the self-compacting mortar (SCM) over time without causing a retardation effect [59]. Increasing the superplasticizer dosage in the formulation of self-compacting mortars does not enhance the mix's fluidity beyond a characteristic value known as the saturation dosage (Figure II. 10).

II.5 Fibre reinforced repair mortars

Several studies have been conducted to investigate the effect of incorporating fibres into the cementitious matrix on the behaviour and performance of mortars.

Fiber-reinforced mortar is one of the materials widely used for repairing old concrete. Fibers are gaining increasing interest in the field of repair due to their ability to enhance mechanical properties, compatibility, and durability, particularly by reducing shrinkage and increasing resistance to cracking [98]. Moreover, in hardened mortar, fibres prevent microcracks from developing into macrocracks [99]. Figure II. 11 illustrates the effect of adding fibres to a concrete specimen subjected to tension. It can be observed that the addition of fibres increases the strength of the concrete and provides it with relatively high ductility.

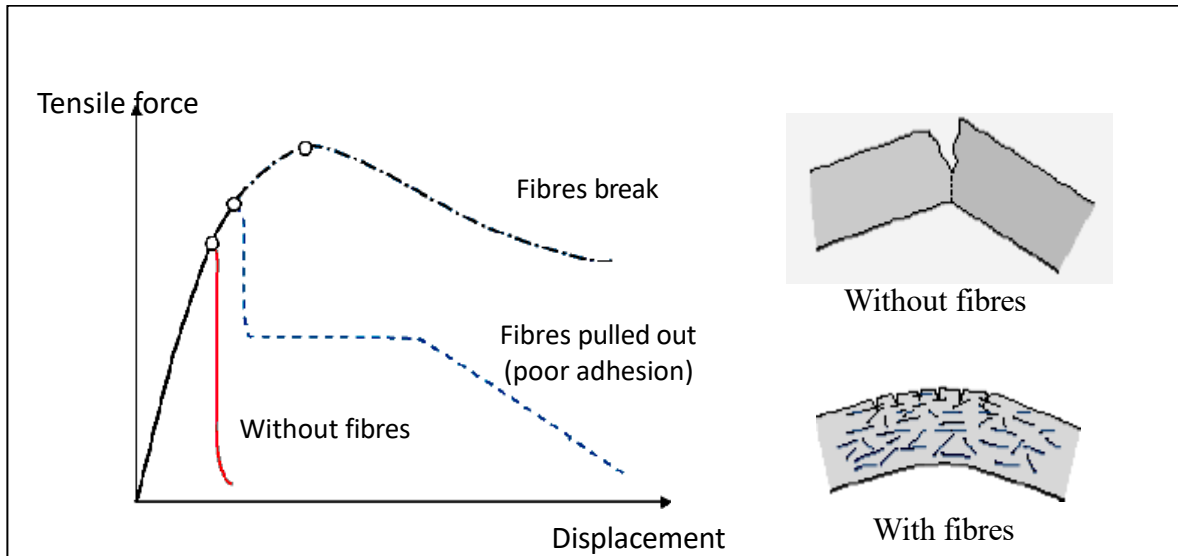


Figure II. 11 Force-displacement curve for a concrete specimen subjected to tension with and without the addition of fibres [100].

The use of fibres in the repair material helps limit the propagation of cracking in the new layer (Figure II. 12). By restricting crack openings, the fibres prevent cracks from reaching the interface between the new and old concrete, thereby reducing the risk of repair detachment and improving adhesion to the substrate [101,102].

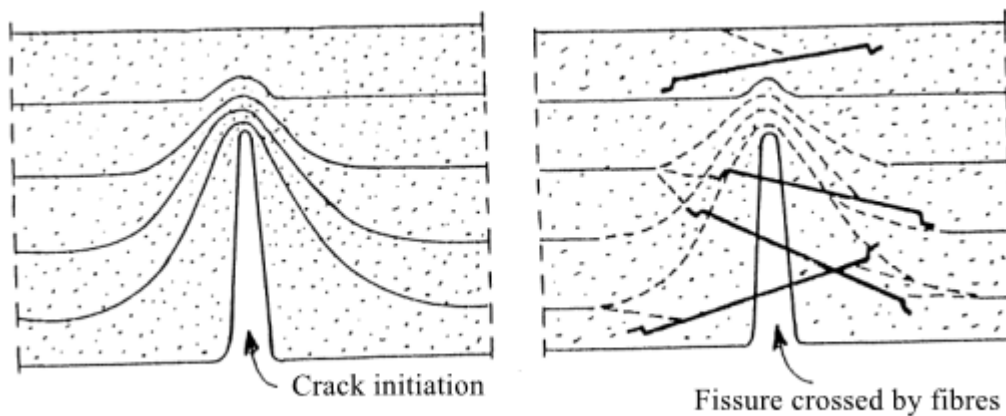


Figure II. 12 Role of fibres in concrete matrix [100]

II.6 Different types of fibres

Fibers are classified based on their origin (natural, synthetic, or artificial), their shape (straight, wavy, needle-like, etc.), their size (macro or micro-fibre), and also their mechanical properties (Figure II. 13). The main fibres used are:

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Mineral fibres: These include various types of fibres (asbestos, alumina, etc.) and are widely used in numerous traditional applications [100].

Vegetable fibres: The main vegetable fibre is cellulose, which is resistant to alkalis. These fibres are also resistant to most organic acids but are destroyed by strong mineral acids. There are four types of plant-based fibres: fibres from hairs, bast fibres, and fibres extracted from the stems of certain grasses. They are often used in paper production and construction panels (wood fibres) [100].



Figure II. 13 Different forms of natural fibre: (a) standard, (b) aggregated, (c) pulp [103]

Synthetic fibres: This category includes various types of fibres such as nylon, polypropylene, acrylic, polyester, etc. These fibres are derived from natural cellulose. Today, most synthetic fibres are derived from petroleum-based products and giant polymers whose structure resembles that of plastics [100].

Artificial fibres: This type of fibre is the most widely used in the industrial field in general and in civil engineering in particular. It includes glass fibres, carbon fibres, steel fibres, and others. Today, they are the most prevalent in the construction industry. Below, we will present the main fibres used to reinforce mortars and concrete [100].

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- **Polypropylene Fibres:** Polypropylene is a crystallizable polymer belonging to the polyolefin family (Figure II. 14). It has been manufactured since 1954 for the textile industry and has seen growing use in this field due to the following advantages: high tensile strength, which can reach up to 800 MPa, and high deformability. These fibres are produced through an extrusion and stretching process, which provides predominant molecular orientation and results in high mechanical properties. These fibres are used in construction for the production of decorative panels, facade cladding for various buildings, as well as in the construction of pipelines and piles.

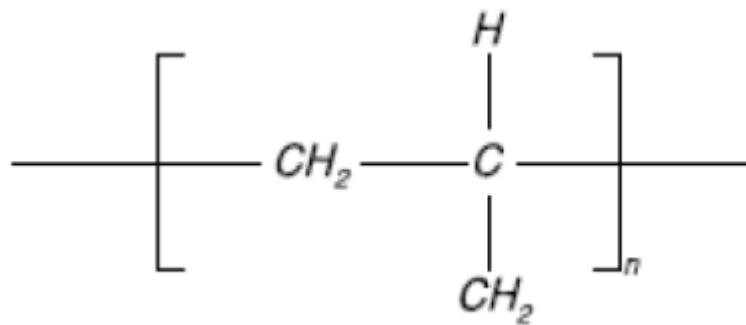


Figure II. 14 Polypropylene fibre [54]

- **Glass Fibres:** These fibres are made from molten glass that passes through a die, heated by the Joule effect, containing 50 to 800 holes with a diameter ranging from 10 to 100 μm . They are commercially available in the form of spools (cut to the desired length) or pre-cut pieces of 3, 6, 12, and 50 mm in length (Figure II. 15). These fibres are generally characterized by the following properties:
 - Good adhesion to the matrix,
 - Availability in various forms (cut, continuous, etc.),
 - Good resistance to moisture and corrosion,
 - Relatively low thermal conductivity.



Figure II. 15 Glass fibres [104]

- **Metal Fibres:** This type of fibre includes steel fibres and amorphous cast iron fibres. The metal fibres used in industrial flooring are most often drawn fibres, typically consisting of wires with a diameter of 1 mm.

The selection of the type of fibres depends on the intended use (reinforcement of mortar or concrete and/or structural repair), their properties (high strength and modulus, good adhesion), their availability, and their cost. However, the most commonly used fibres in repair mortars are generally synthetic fibres of organic origin (*Figure II. 16*). These fibres are randomly oriented within the cementitious matrix. They have the ability to control the propagation of cracks caused by shrinkage and lead to greater post-cracking strength due to their bridging effect [105].



Figure II. 16 SEM (Scanning Electron Microscope) image showing the bridging of cracks by polypropylene fibres [105].

II.7 Influence of fibre percentage

The introduction of fibres into concrete affects its performance in both fresh and hardened states, depending on the dosage, length, and shape of the fibres used. Chen and Liu evaluated the effect of fibre type on the workability of fibre-reinforced concrete. Three types of fibres were considered for comparison: steel fibres, polypropylene fibres, and carbon fibres. The least effect on concrete slump was observed with polypropylene fibres, while the most significant effect was recorded for steel fibres [106]. Additionally, it was shown that the addition of polypropylene fibres (PPF) does not strongly affect the air content or the fresh density of concrete due to the low density of polypropylene fibres, unlike other types of fibres such as steel fibres.

Workability: Although the introduction of polypropylene fibres at low dosages does not significantly affect the properties of fresh concrete, this minor influence becomes considerable, especially when fibres are introduced in high concentrations. In this regard, some previous studies have shown that the introduction of polypropylene fibres at significant concentrations leads to a loss of fresh concrete properties. *Figure II. 17* shows the spread results of fresh concrete made with different combinations of fibre types and lengths, including polyvinyl alcohol, cellulose, nylon, and polypropylene fibres. As shown in *Figure II. 17 (a)*, the control concrete without fibres indicates a spread value of 735 mm. In contrast, the introduction of a high percentage of fibres caused a significant decrease in workability. This reduction is particularly noticeable for concrete containing 19 mm polypropylene (PP) fibres, while other mixtures with shorter fibre lengths showed relatively better spreads. To overcome the loss of workability, it was proposed to mix polypropylene fibres with nylon fibres, which helped improve workability [107].

Through various investigations published on fibre-reinforced concrete, it appears that the fibre percentage is one of the most significant factors affecting the rheology of polypropylene fibre-reinforced concrete. Mazaheripour et al. reported that increasing the percentage of polypropylene fibres from 0.1% to 0.3% in self-compacting lightweight concrete led to a significant drop in spread (*Figure II. 18 (a)*) and U-BOX filling capacity (*Figure II. 18 (b)*).

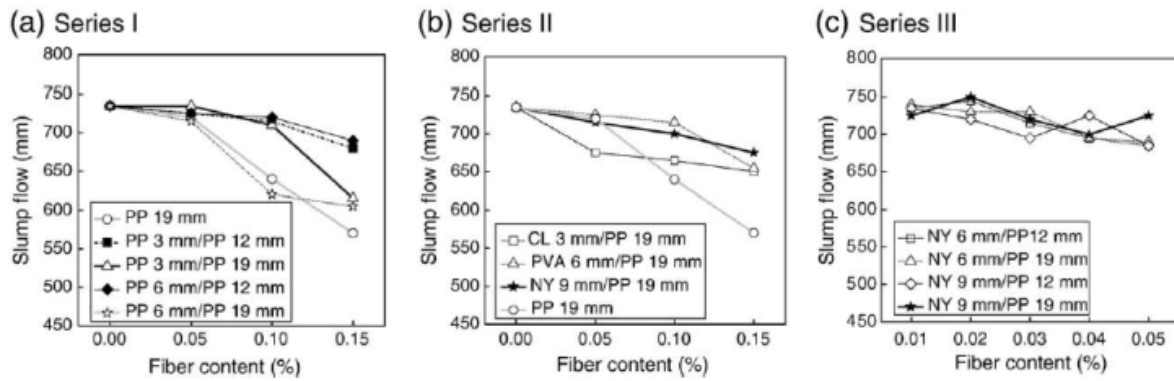


Figure II. 17 Evolution of slump flow in function of fibre dosage [107]

Beyond 0.15% fibre content, the V-funnel flow time also increased (*Figure II. 18 (c)*). Additionally, at a dosage of 0.3%, concrete blockage was observed during the U-BOX test [108].

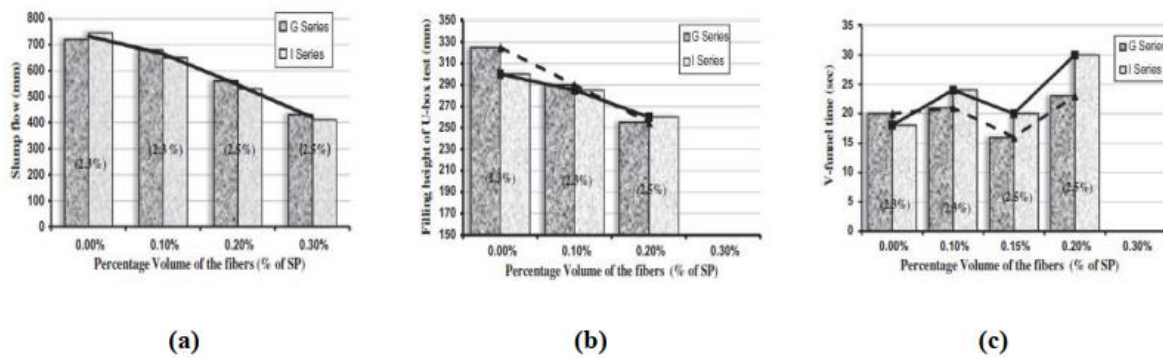


Figure II. 18 Evolution of slump flow (a), filling capacity (b), and flow time (c) as a function of fibre percentage [108].

Ramezaniyanpour et al. [109] explained the loss of workability induced by the introduction of fibres is partly due to the amount of air trapped in the pores formed between the different constituents within the concrete, which hinders its smooth flow. It is worth noting that the loss of workability due to increased fibre dosage has also been reported for cement pastes. Zhang et al. conducted a study on the effect of polypropylene fibres on the properties of fresh cement pastes. The results obtained by testing three fibres of different lengths (3, 6, and 12 mm) showed that, for each length, the fluidity of the paste gradually decreases as the fibre dosage increases from 0 to 0.5% [110]. Others researchers concluded that incorporating small dosages of polypropylene fibre (0.02% and 0.03%) showed an enhancement in workability however, increasing PPF (0.06% and 0.09%) dosage led to a decrease in workability [111].

Rheological parameters: Regarding the rheological parameters of fibre-reinforced pastes, it has been shown that the apparent viscosity increases with the length and dosage of polypropylene

Chapter II: Self-compacting repair mortars

fibres. Indeed, increasing the length and dosage of fibres negatively affects the homogeneity of the mixture by promoting flocculation and making the breakdown of bonds within the formed flocs more difficult (Figure II. 19). This automatically leads to an increase in the yield stress and apparent viscosity [110]. To address this flocculation issue, the use of a polycarboxylate-based superplasticizer (PCE) has been recommended [112]. This proposal is based on the results of previous studies that prove that adding a superplasticizer increases the slump of ordinary concrete, directly influencing these rheological parameters (yield stress and viscosity decrease) [113]. This type of admixture is absorbed on the surface of cement particles, thereby eliminating particle flocculation and improving the fluidity of the paste [114]. Indeed, Zhang et al. [110] demonstrated that the introduction of 0.15% PCE in a cement paste reinforced with polypropylene fibres improves its fluidity (higher slump) by reducing its rheological parameters (viscosity and yield stress). Furthermore, other researchers have proposed increasing the paste volume in the formulation of fibre-reinforced concrete or introducing pozzolanic powders to enhance rheological performance [115]. Yield stress and plastic viscosity were found to decrease by adding (0.02% and 0.03%) PPF in self-compacting repair mortar however, adding more fibres (0.06% and 0.09%) rises both rheological parameters [111].

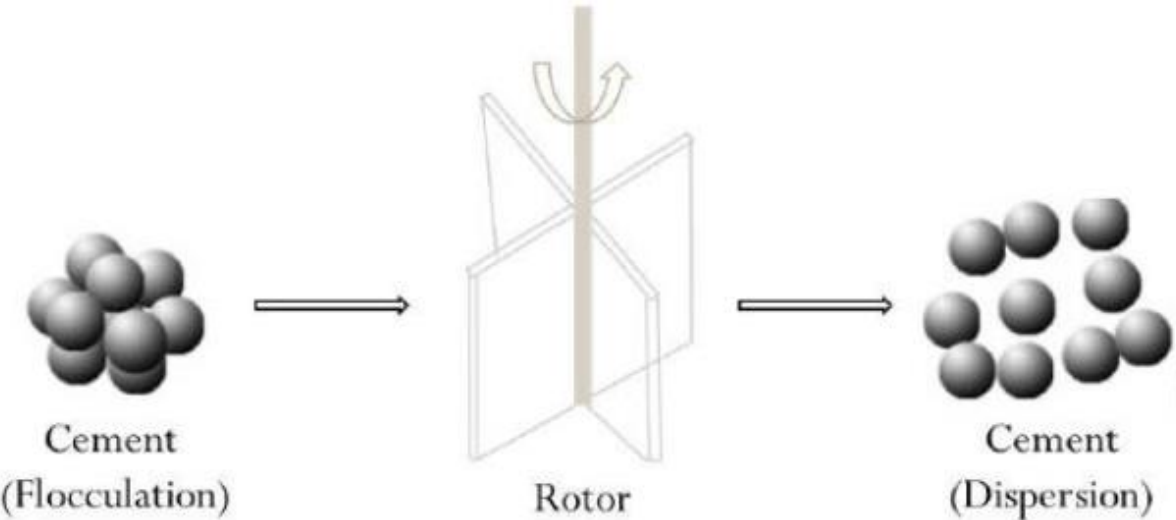


Figure II. 19 Cement particle deflocculation under higher shear stress [110]

Absorption: In general, reinforcing concrete with fibres affects its water absorption capacity depending on the type of fibres used. Indeed, it is known that polypropylene fibres have a positive effect on water absorption, and their introduction into concrete reduces the water absorption rate more effectively than steel fibres. Rashid reported that at 0.4% and 0.6% polypropylene fibre content, water absorption decreases by 3% and 8%, respectively, compared

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to the control concrete. This result is consistent with the findings of Sun et al., who also reported that water penetration in concrete decreases with increasing fibre dosage [116].

Porosity: The increase in polypropylene fibres often leads to an improvement in terms of durability. However, some studies have reported that a very high fibre content can result in increased porosity. Karahan and Atiř demonstrated that increasing the fibre dosage leads to a porosity increase of 6%, 18%, and 28% for polypropylene fibre dosages of 0.05%, 0.10%, and 0.20%, respectively [117].

Compressive strength: In the field of civil engineering, the compressive strength of concrete is one of its fundamental properties. For this reason, most published research on fibre-reinforced concrete has taken this factor into account. Although some studies have reported that concrete strength increases slightly when polypropylene fibres are introduced at an appropriate dosage, fibre-reinforced concretes generally have compressive strengths comparable to those of non-fibered concretes. It should be noted that the optimal fibre dosage varies from one fibre-reinforced concrete to another, depending on the shape and length of the fibres used.

At low fibre dosages in concrete, the improvement in its compressive strength remains very limited or even negligible. This observation applies to several types of polypropylene fibres, as demonstrated by Yin et al. [118] (Figure II. 20). Indeed, they introduced 4 kg/m³ of fibres into concrete, and the resulting compressive strengths were comparable to those of non-fibered concrete.

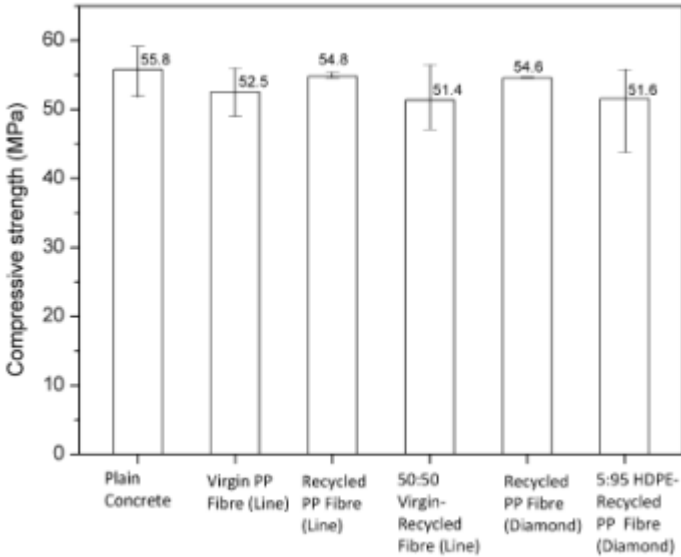


Figure II. 20 The effect of natural and recycled PP fibres on the compressive strength of concrete [118]

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The optimal fibre dosage in concrete is strongly related to the distribution of the fibres within the mix. Therefore, proper fibre distribution is necessary to ensure fibre-reinforced concrete with good mechanical performance. Noushini et al. [119] introduced five types of synthetic fibres into a geopolymer concrete at a dosage of 0.5% and observed an average reduction of 1% to 7% in the compressive strength of concrete reinforced with polypropylene fibres compared to the control concrete. This was primarily attributed to the poor distribution of fibres within the cement matrix, which led to increased porosity in the concrete, negatively affecting its mechanical strength [118]. This finding has also been reported for Portland cement-based concretes, where optimizing the mix formulation was strongly recommended to ensure proper fibre distribution [120–122]. Bendjilali et al. [111,123] investigated the effect of PPF percentage (0.02%, 0.03%, 0.06%, 0.09% and 0.12%) on the evolution of compressive strength of self-compacting mortars and reported that 0.06% is the optimal dosage that revealed to the highest compressive strength.

Flexural strength: The flexural strength of concrete is an important property that affects the mechanical behaviour of concrete structures and their durability. Polypropylene fibre-reinforced concretes are characterized by a tensile behaviour that differs from that of non-fibre concretes. Fiber-reinforced concretes exhibit greater ductility compared to non-fibre concretes. Additionally, the tensile strength of concrete can be significantly improved by the introduction of fibres. Flexural strength increases by 20 to 57% when 0.2% to 0.4% polypropylene fibres are introduced, respectively [124]. However, for lower fibre contents, such as 0.1%, 0.2%, and 0.3%, the flexural strength of concrete increases slightly, by 4.9%, 8.6%, and 10.7%, respectively (*Figure II. 21*) [108]. Indeed, polypropylene fibres reinforce concrete by limiting crack propagation and stabilizing the cementitious matrix after cracking [125]. Bendjilali et al. [111,123] studied the effect of PPF percentage (0.02%, 0.03%, 0.06%, 0.09% and 0.12%) on the evolution of flexural strength of self-compacting mortars and reported that 0.12% is the optimal dosage that revealed to the highest flexural strength.

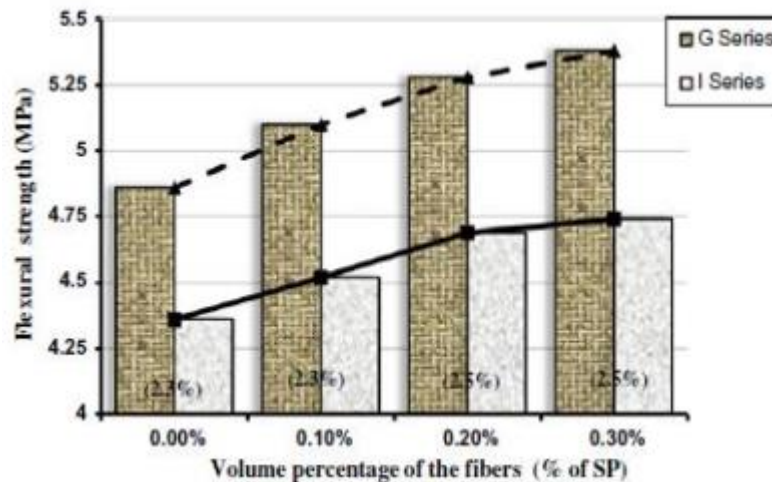


Figure II. 21 Evolution of flexural strength of fibre-reinforced self-compacting concrete in function of fibre dosage [108].

II.8 Fibre reinforced self-compacting concrete/ mortar in repair applications

The use of fibres in self-compacting concrete (FRSCC) and/or mortar (FRSCM) has numerous applications. Indeed, these applications are summarized in Table II. 1 below:

Table II. 1 The application of fibre reinforced concrete/ mortar.

Applications	Benefits provided by the addition of fibres in concrete
Pipelines and thin shells under low stress	- Improved performance of elements at early ages - Control of dimensional variations and reduction of cracking
Floor slabs, concrete pavements, manufactured slabs, and structural elements subjected to bending	- 40% reduction in crack width - Increased stiffness after cracking - Improved shear resistance - Enhanced wear resistance
Structural elements subjected to compression (columns, piles, foundations, etc.)	- Increased ultimate load - Prevention of catastrophic failures
Structures subjected to dynamic loads (e.g., airport runways)	- Increased energy absorption - Longer impact duration - Significant modification of the material's stress-strain behaviour
Repair of road surfaces and bridge decks	- Improved impact resistance - Increased deformability
Parts exposed to large temperature variations or very high temperatures	- Effective replacement of refractory linings - Reduced repair costs of refractory elements

<p>Stabilisation of rock faces, slopes, tunnels, and underground galleries</p>	<ul style="list-style-type: none"> - Elimination of the need for mesh fixing - Reduced repair and stabilisation costs of rock faces and slopes
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II.9 Conclusion

In this chapter, we have briefly described a new technology mortar, widely used for concrete repair. Self-Compacting Mortar (SCM) facilitates application since it flows under its own weight with a sufficient rate and easily bypasses obstacles in confined areas (high reinforcement density, corners, etc.).

The literature has also shown that SCM differs from Ordinary Mortar (OM) due to the presence of significant amounts of fine particles and superplasticizers. These components give it self-compacting properties, including high fluidity, strong resistance to segregation, and minimal bleeding. However, developing an optimal SCM formulation remains a challenging task.

Today, various composition techniques have been developed for SCM formulation. However, all methods rely on an experimental approach and require a precise specification sheet detailing the desired performance of the mortar in both its fresh and hardened states. As well as the interest in incorporating mineral additives to improve the performance of self-compacting mortars and concretes.

This literature review also highlighted the advantages offered by the incorporation of fibres in the repair mortar. Fibres help to limit crack propagation, reduce the probability of repair detachment, and improve adhesion to the substrate. In addition, polypropylene fibres offer other benefits, such as their relatively low cost, flexibility, and high dispersion within the matrix.

The third chapter is a literature review focusing on the effect of marble powder and hot climate on the properties of concrete and mortar, as well as the compatibility of repair mortars with the concrete substrate.

Chapter III

Effect of marble powder, effect of hot climate, compatibility of repair system

III.1 Introduction

The cement industry sector is responsible for 5% to 8% of the total amount of CO₂ emitted into the atmosphere [126]. The most effective solution is to reduce the amount of clinker produced by replacing it with supplementary materials that have properties similar or equivalent to clinker. Blast furnace slag, fly ash, silica fume, natural pozzolan, and limestone fillers are the most commonly used supplementary materials in the cement industry.

Mortars and concretes containing supplementary materials have improved properties, such as low heat of hydration, low permeability, reduced clinker consumption, and a lower environmental impact due to the reduction of CO₂ emissions [15,16,89,127,128]. Through their physical and physico-chemical effects, they help enhance the performance of mortars and concretes both in the fresh and hardened states.

The selection of appropriate repair materials depends on the material properties and the behaviour of the composite section under the anticipated service exposure conditions [44]. In hot climatic conditions, the choice becomes even more critical, since elevated temperatures accelerate water evaporation, increase the risk of plastic and drying shrinkage cracking, and may adversely affect the hydration process of cementitious materials.

Choosing an optimal repair material is one of the critical factors determining the success of any repair process. Surface preparation, application method, construction practices, and inspection are also decisive factors in the selection process. However, selecting an optimal repair material in terms of cost, performance, and risk is not an easy task. It requires knowledge of the user's expectations for the repair process and the material's behaviour in both hardened and unhardened states under the intended service and exposure conditions [129,130].

Repair materials can have widely varying costs and performance levels. Before an engineer attempts to select a specific repair material, it is essential to take the time to consider the type of behaviour expected from the repaired structure [131]. Furthermore, in the case of repairing concrete structures and components, since most materials are applied to an existing concrete substrate, it is necessary to consider not only the performance properties of the repair material but also its compatibility with the existing concrete [132].

III.2 Effect of marble powder on the performance of cementitious materials

Marble powder (MP) as waste material, produced during the cutting process of marble rocks, should not be ignored due to its huge quantity and the serious environmental problems encountered [78,79]. It has a negative influence on both people’s social and industrial activities. Marble is a metamorphic stone formed by the transformation of limestone (calcite-CaCO₃). 30%- 40% of processed marble in factories is a production waste [13]. Its utilization in the industry yields substantial returns in terms of economic and environmental performance [80]. MP could be incorporated in concrete, cement or synthetic resins [81].

III.2.1 Workability properties

Workability results of research studies have been reported by many researchers, showed that using marble powder to replace cement lead to increase workability [133,134]. Dada et al. [16] noted that the introduction of more than 5% MP leads to an increase in the slump and a decrease in the flow time. An increase rate of 25% in slump is obtained with the incorporation of 30% (Figure III. 1).

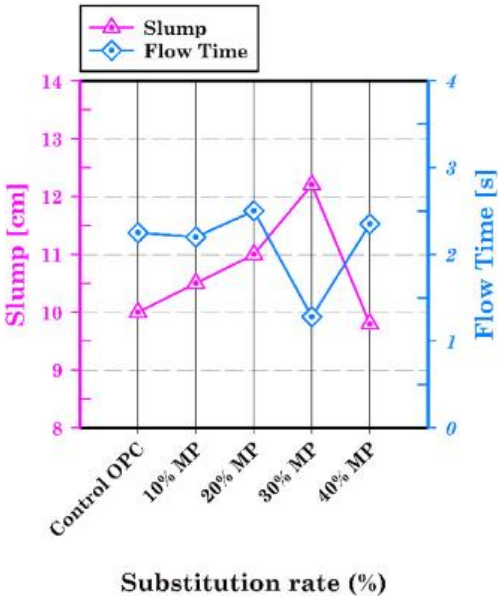


Figure III. 1 Effect of MP on workability properties of concrete equivalent mortar (CEM) [16]

However, Choudhary et al. [135] recorded a decline in fresh behaviour in the presence of MP. Belaidi et al. [67] studied the effect of marble powder on fresh mortar and concluded that the use of MP increased remarkably the slump flow diameters of self-compacting mortars and

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decreases flow time. Yamanel et al. [136] studied the incorporation of marble powder into mortar. They concluded that replacing cement with marble powder contents ranging from 5% to 20% leads to an increase in workability. Boukhelkhal et al. [137] studied the effect of adding marble powder (MP) on the properties of self-compacting concrete in its fresh state (Figure III. 2). They observed an improvement in workability with the increase in the cement substitution rate by MP. Similar results were recorded by replacing cement with MP in self-compacting repair mortars conducted by Bendjilali et al. [111,123].

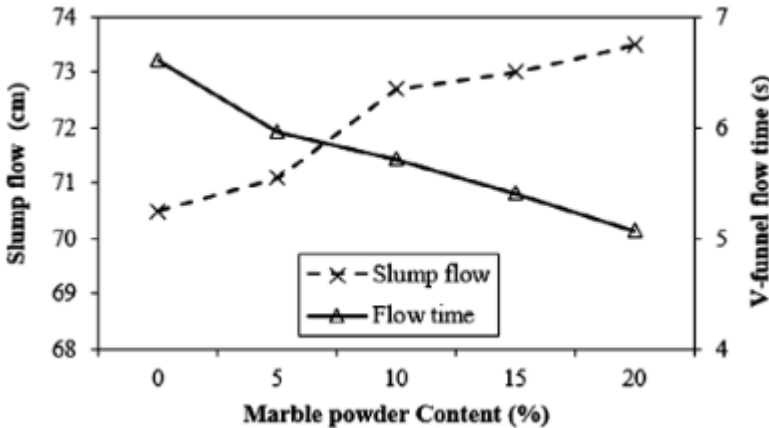


Figure III. 2 Effect of marble powder on slump flow and v-funnel flow time of SCC [137]

III.2.2 Rheological properties

Many researchers investigate the inclusion of MP as a substitution of cement and resulted in a decrease both yield stress and plastic viscosity of mortar and concrete [15,67]. Dada et al. [16] resulted in beneficial effect of substitution of cement by MP. From (Figure III. 3) it is clear that the presence of MP reduces the yield stress and plastic viscosity. That could be due to the MP particles which are characterized by less angular and coarse shape as well as the lesser requirement for superplasticizers and the increase in the volume of paste caused by the difference in the density of cement and that of MP.

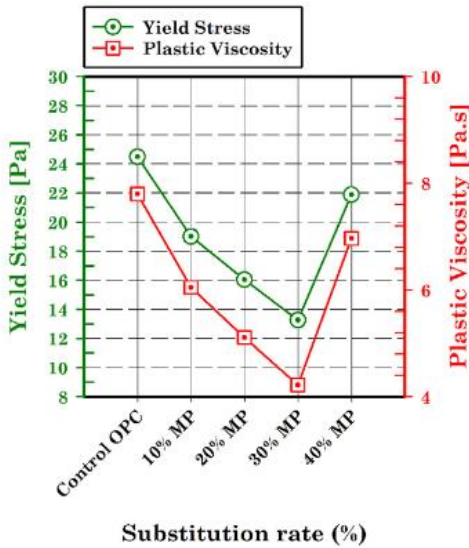


Figure III. 3 Effect of MP on rheological parameters of concrete equivalent mortar (CEM) [16]

Boukhelkhal et al. [137] studied the addition of MP (5%, 10%, 15% and 20%) on the rheological properties of self-compacting concrete and reported a decline in both yield stress and plastic viscosity (Figure III. 4). Corinaldesi et al. [138] studied the effect of introducing 10% and 20% PM as a replacement for cement or sand in pastes and mortars. They observed that pastes prepared with PM, a superplasticizer, and a water-to-cement ratio (W/C) of 0.4 exhibited higher yield stress. They noted the same phenomenon for cement pastes prepared with PM and a W/C ratio of 0.5 but without the superplasticizer. In contrast, when the W/C ratio was 0.5 and the superplasticizer was added, the yield stress was very low. Bendjilali et al. [111] used MP to substitute cement in self-compacting repair mortars and resulted in a decline in both rheological properties.

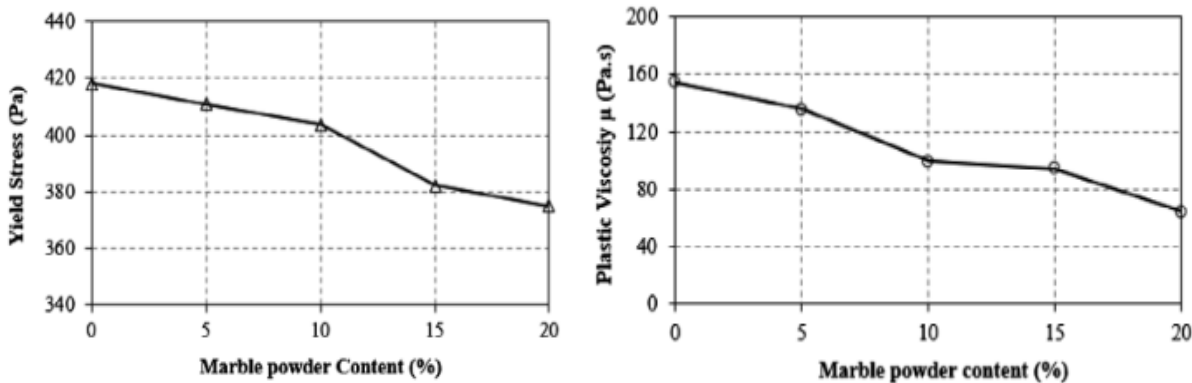


Figure III. 4 Effect of MP on rheological parameters of self-compacting concrete [137]

III.2.3 Heat of hydration

The heat of hydration is the amount of heat, in joules per gram (J/g), released by the hydration of cement over a given period of time and at a specific temperature [139].

Prosek et al. [140] investigated the hydration of PC pastes with MP ranging from 5% to 50% as a replacement for cement. hydration heat flux was measured for 7 days at a constant temperature of 20°C. Calorimetry results revealed that the more MP in a mixture, the less cumulative heat was released during the first 7 days of hardening. Figure III. 5 indicates that presence of waste marble slurry (WMS) inhibits rapid hydration of C₃S. On the other hand, heat flux was slightly accelerated by the presence of WMS for the 20–40 h period.

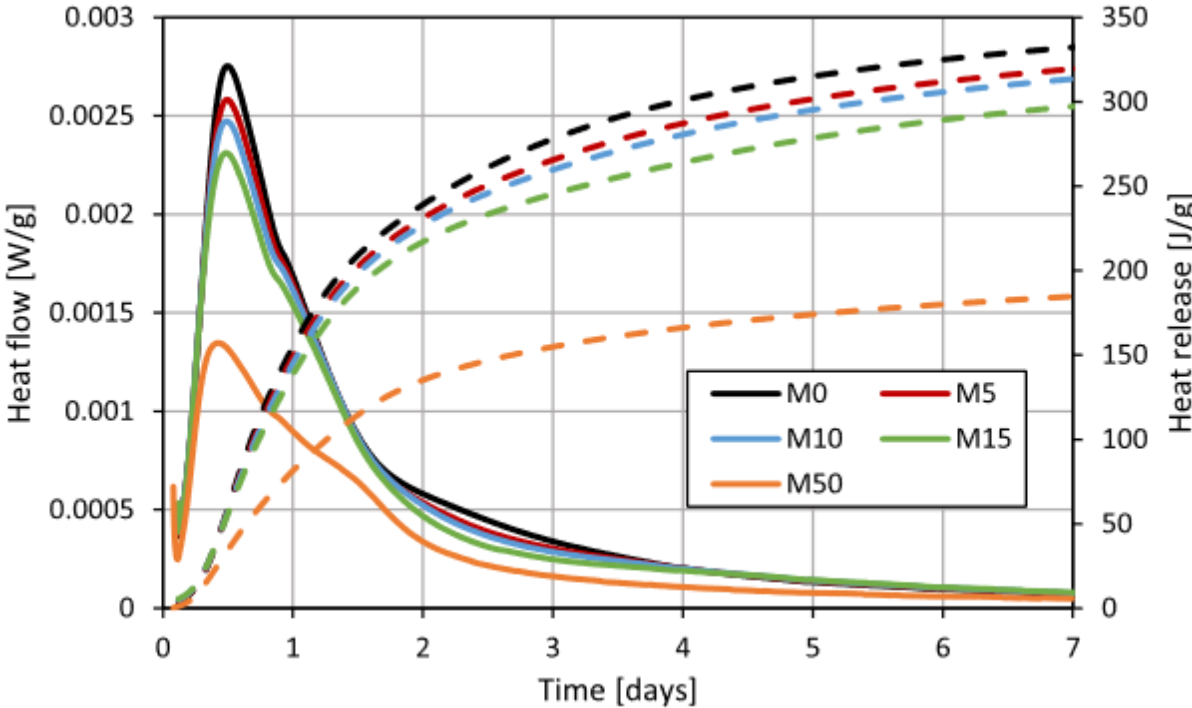


Figure III. 5 Hydration heat flow (solid lines) and cumulative heat (dashed line) of cementitious paste enhanced with WMS [140]

Péra et al. [141] found similar results when studying the effects of CaCO₃ on C₃S hydration. In this study, PC with a high C₃S content (74.6 wt.%) was used with MP, which is mostly CaCO₃ (95 wt.%). The presence of MP influenced not only cumulative heat but also heat flow development.

III.2.4 Setting time

Setting time is also influenced by MP incorporation. Some authors concluded that the use of over 20% MP causes a delay in setting time [142–145,133]. When augmenting waste marble powder content, C₃S content is reduced and thus led to decreasing cement hydration (it means that setting becomes slower) [18]. However, Toubal et al. [146] recorded that MP did not have a significant effect on setting times of the fresh cement paste. It is because the fineness of MP (3869.46 cm²/g) is similar to that of PC (3571.78 cm²/g).

III.2.5 Mechanical strength

Compressive strength is the most required mechanical property in concrete and mortar. Compressive strength decreases with increasing MP as a replacement for cement in all ages of 3, 7, 28, and 65 days [146] (Figure III. 6).

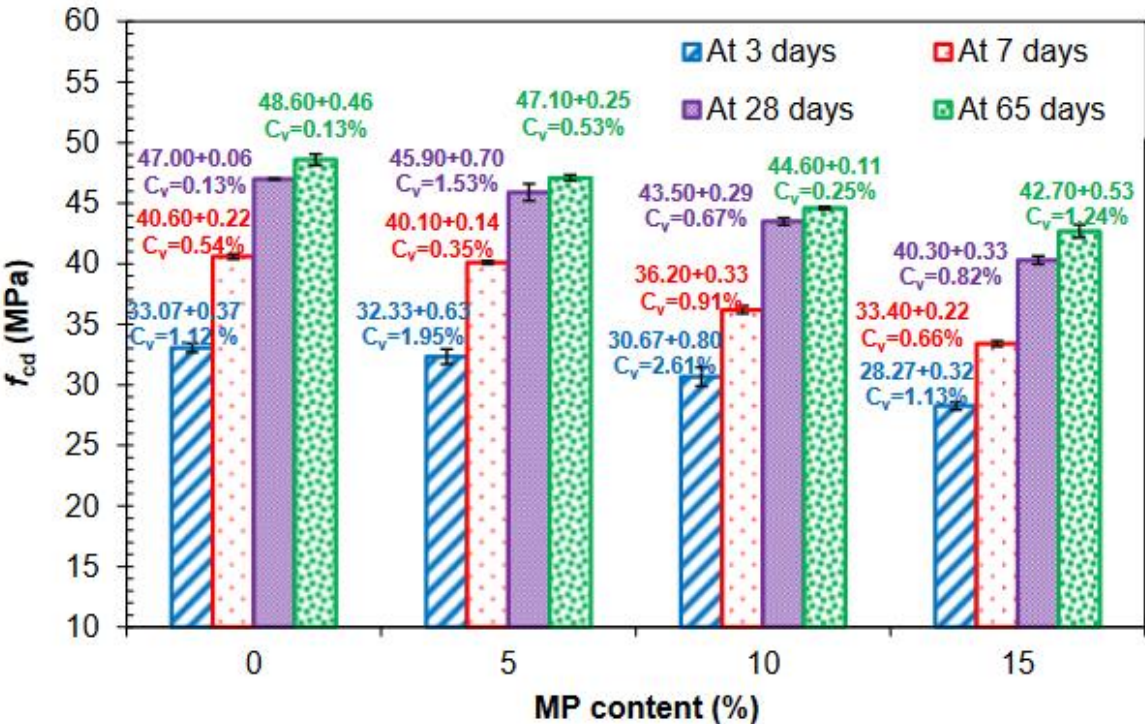


Figure III. 6 Effect of the marble powder content on the compressive strength of cement paste at different ages [146]

This reduction is attributed to the phenomenon of dilution of pozzolanic reactions [15,16,67,79,136,147–151]. The majority of studies have shown that the flexural strength decreases with the increase in the rate of substitution of cement by MP [133,136,151]. Ergun reported that the substitution of 5% of the cement with MP improves the compressive strength

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of conventional concrete due to its high fineness (5960 g/cm²) [152]. In a previous study, the effect of marble powder on the properties of SCC was investigated [153]. The results show that MP exhibits good compressive performance. The compressive strengths were comparable or even superior to the reference SCC (in the case of SCC with 10% MP). A study conducted by Corinaldesi et al. [138] aimed at examining the effect of marble powder on mortars and concrete showed that, in terms of compressive strength, the maximum value was obtained with the mixture containing 10% MP as a partial replacement for sand. Bendjilali et al. [111] studied the effect of using up to 30% of MP in self-compacting repair mortars and concluded that adding up to 20% MP to mortar with 0.06% PPF resulted in compressive strength comparable to that of mortar with 100% cement.

III.2.6 Modulus of elasticity

Rodrigues et al. [154] studied the impact of cement substitution by MP in concrete on the modulus of elasticity with different dosages ranging from 5% to 20% (steps of 5%). The results show that modulus of elasticity declines as the replacement rate augments, with a maximum loss about 10.3% at 20% of MP (Figure III. 7). Other researchers have obtained comparable results for static and dynamic moduli of elasticity [153,155] (Figure III. 8). Bendjilali et al. [123] investigated the use of MP to replace cement at 10%, 15%, 20%, 25% and 30% and reported that increasing MP replacement led to decline elasticity modulus at 28 and 90 days.

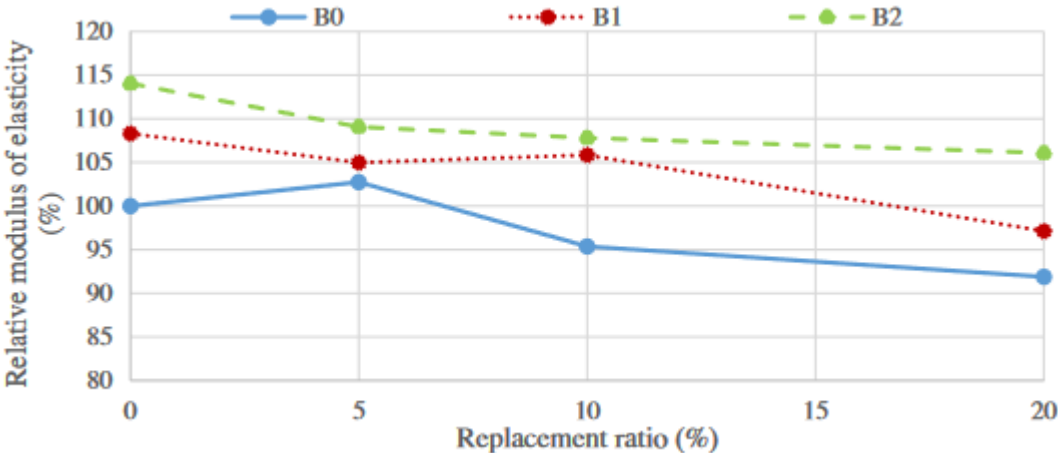


Figure III. 7 Relative modulus of elasticity of concrete mixes incorporated MP [154]

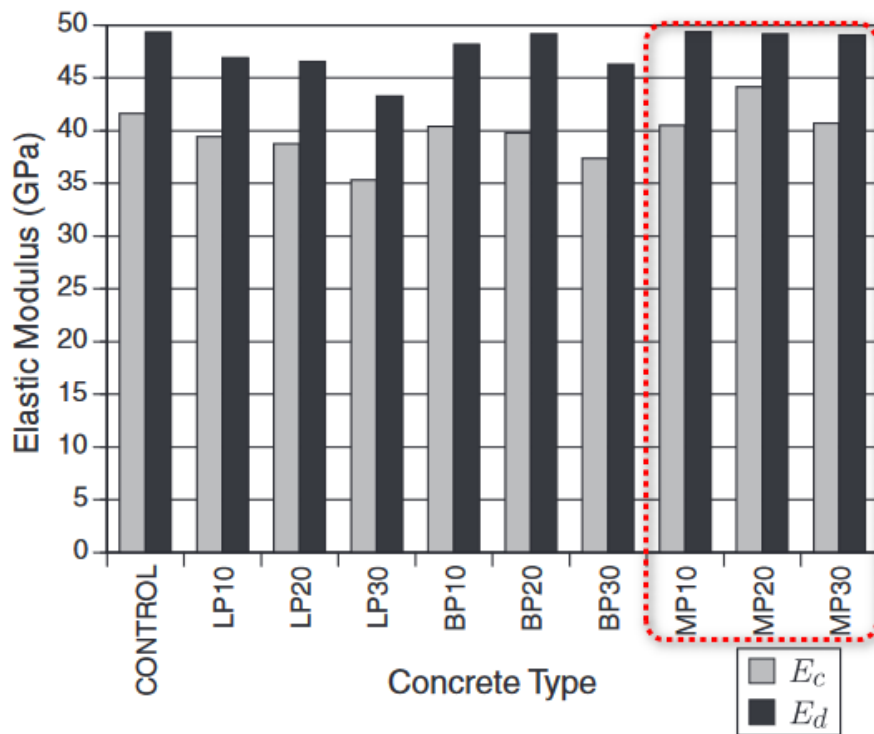


Figure III. 8 Static and dynamic elastic modulus of SCC with LP, BP, and MP [153].

III.2.7 Microstructure analysis

Numerous researches showed that MP-blended cement specimens are denser and less porous than control specimens. The microstructure of pastes is composed of amorphous particles of calcium silicate hydrate (CSH) and calcium hydroxide (CH) crystals that appear in massive layers. Ettringite (E) needles are located in pores; then the paste is totally hydrated, and all voids are completely filled [147,156]. SEM analysis of specimens with and without MP performed by Kumar et al. [157] indicated that the morphology is distinct in terms of pore structure (Figure III. 9). we observe a heterogeneous matrix with the presence of cracks and large pores in control mix [158]. In addition, there are large crystals of calcium hydroxide (CH) distributed irregularly in the matrix. In comparison, with substitution of cement by 5.0% of MP the matrix seems to be comparatively more homogeneous with a lesser number of pores and negligible cracks. This is due to the filling effect of MP particles in the concrete [154,159].

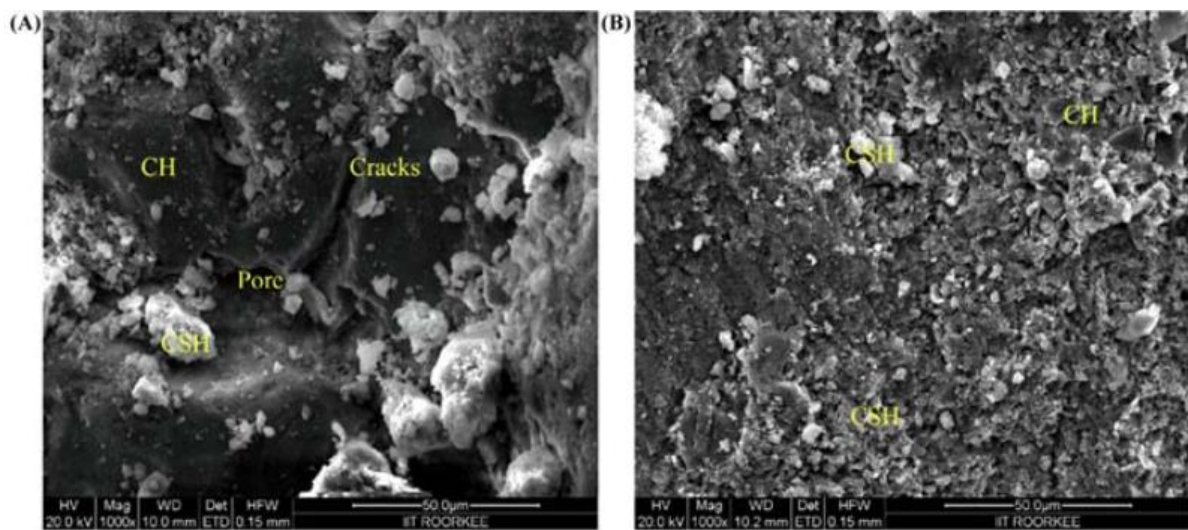


Figure III. 9 Micrographs of (A) control mix and (B) specimen in the presence of 5.0% MP [157].

III.2.8 Water absorption

It has been shown that MP as substitution to cement reduces concrete water absorption values at lower W/C ratios [134,160–163]. However, Boukhelkhal et al. [128] found that that the increase in the amount of substituted MP leads to an increase in the water absorption of SCC at 28 days. The incorporation of MP from 5% to 20% increases the water absorption rate by from 9.7% to 22.6%, respectively (*Figure III. 10*). Similar conclusion was made by Bendjilali et al. [123] when incorporating MP in self-compacting repair mortars from 10% to 30%. Water absorption by immersion of SCC was also found to increase with increasing MP amount (*Figure III. 11*).

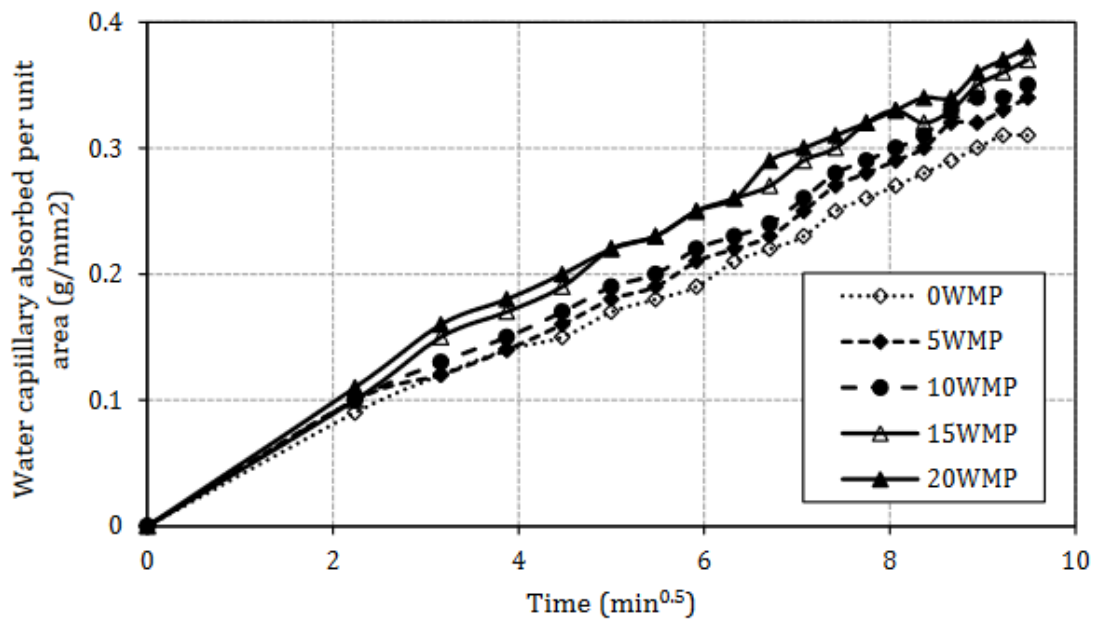


Figure III. 10 Effect of MP on capillary absorption of SCC [128]

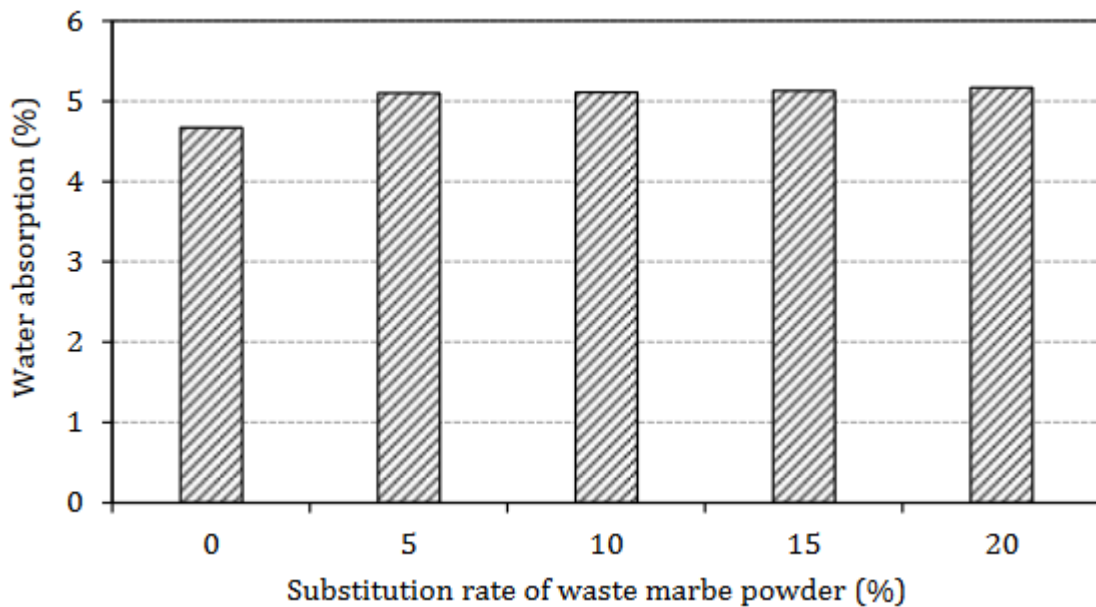


Figure III. 11 Effect of MP on water absorption by immersion of SCC [128]

III.2.9 Shrinkage

Yamanel et al. [136] studied the effect of MP as cement replacement on the shrinkage of mortars. The results given in Figure III. 12 show that the shrinkage of all mortars increased with increasing time because shrinkage is a function of cement hydration. However, replacing MP with cement resulted in a partial reduction in shrinkage values when compared to the control cement mortar. This reduction in shrinkage increases with the increase of the level of substitution of cement with MP. This is due to a decrease in cement content caused by the partial

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replacement of MP with cement. Vardhan et al, Li et al, Valdez et al., and Hlubocky' and Prosek [78,164–166] found similar results of reduced drying shrinkage for conventional and self-compacting concrete-based MP.

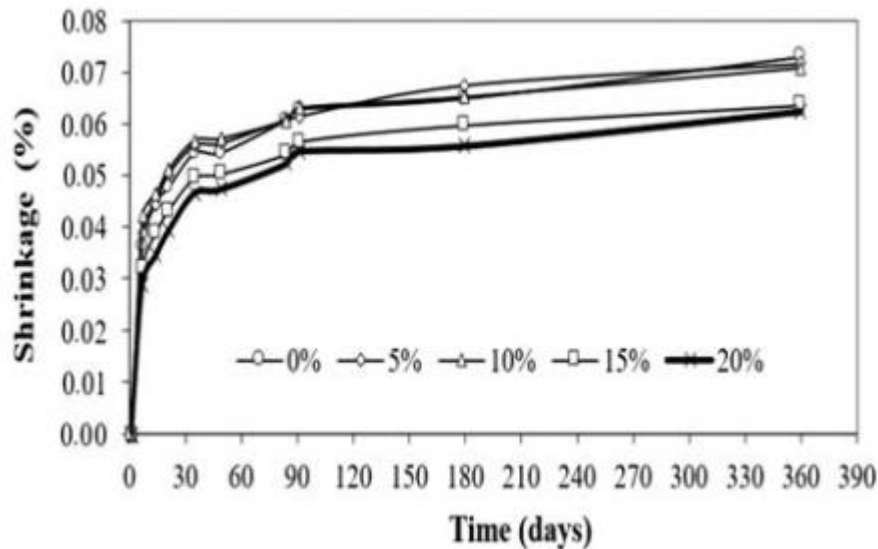


Figure III. 12 Shrinkage results of concrete mixtures containing MP as cement replacement [136].

III.2.10 High temperature resistance

Yamanel et al. [136] investigated the fire performance of mortar containing MP as cement substitution. The results of compressive strength tests show that all mortars gained strength after being exposed to 300°C ranged between 3% and 9%. All mortars lost their strength when the temperature was raised to 600°C and 900°C as it is illustrated in Table III. 1.

III.2.11 Cost

Many authors have studied the cost efficiency analysis of MP-based concrete. MP is a waste material and therefore is freely available, except for the transportation costs. Results obtained by Ince et al. [167] showed that incorporating MP resulted in a slight decrease in the cost efficiency factor of concrete incorporating MP. Singh et al. [168] analysed the costs for 1 m³ concrete with 15% cement replacement by MP and with 25% sand replacement by MP. The first case (MP as cement replacement) indicates a benefit of 9.08%, while the second case (MP as sand replacement) incurs a loss of 3.4%.

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Table III. 1 Compressive test results after high temperature (MPa) (%) [169]

Mix no	20 °C	300 °C/20 °C	600 °C/20 °C	900 °C/20 °C
M-0	52.7	54.6 (1.04)	31.9 (0.61)	18.1 (0.34)
M-5	52.1	53.7 (1.03)	29.9 (0.57)	18.6 (0.36)
M-10	48.7	51.4 (1.06)	27.8 (0.57)	15.8 (0.32)
M-15	46.3	49.1 (1.06)	28.8 (0.62)	16.4 (0.35)
M-20	42.8	46.7 (1.09)	27.2 (0.64)	15.5 (0.36)

III.2.12 Environmental effect

The main contributor to the carbon footprint of mortar/concrete production is the cement content [170,171]. The cement content accounts for more than 90% of the carbon footprint of mortar/concrete (the manufacture of 1.0 ton of cement generates about 0.9 ton of CO₂). Because of the addition of MP, the reduction in cement content would significantly reduce the carbon footprint and thus improve the environmental sustainability [78]. According to Arel [172], using MP in concrete production reduces environmental pollution and benefits the economy. The author reported that replacing cement with 5% and 10% MP improves the mechanical properties of concrete and reduces the costs of concrete production and the CO₂ emissions of cement production by about 17% and 12%, respectively [160].

Thanks to this fact, usages of marble wastes in concrete have been researched by several researchers over the past years. Thus, it can be mentioned that using waste marble as powder and recycling it, turns these negative effects into positive ones [18].

III.3 Hot climate and its effect on concrete and mortar

Climate refers to the set of atmospheric conditions (temperature, relative humidity, wind speed, sunlight, and precipitation) over a specific location.

According to ACI (American Concrete Institute) [173], hot weather is defined as any combination of the following conditions that tend to affect the quality of concrete in both its fresh and hardened states:

- High ambient temperature

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- Elevated concrete temperature
- Low relative humidity
- Wind speed
- Solar radiation

Based on the average relative humidity, hot climates can be classified into three categories [174]:

- Hot and humid climate: $RH \geq 85\%$
- Hot climate with moderate humidity: $50\% < RH < 65\%$
- Hot and dry climate: $RH < 40\%$

III.4 Climatic parameters affecting concrete quality

III.4.1 Ambient temperature

Temperature is a physical quantity whose variations create sensations of warmth and coolness. It fluctuates with the seasons, altitude, latitude, and proximity to the sea. An increase in this parameter beyond 25°C generally promotes the evaporation of water from the surface of the concrete and its drying. This also leads to an acceleration of setting and hardening without necessarily improving long-term strength [175,176].

Tests conducted on cement mortar have shown that the initial setting time is reduced by half when the temperature increases from 28°C to 46°C [177].

As a result, builders and engineers must pay close attention to controlling climatic conditions in general and temperature in particular throughout all stages of material storage, mixing, transportation, delivery, placement, and curing to ensure high-quality structural concrete.

III.4.2 Relative humidity

Relative humidity refers to the percentage of air saturation with water. If the relative humidity is 0%, the air is completely dry and contains no water molecules. If it is at 100%, the air is fully saturated with water.

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In general, changes in ambient temperature are accompanied by more or less significant variations in relative humidity. It has been reported that significant daily fluctuations in relative humidity cause condensation-drying cycles on exposed concrete surfaces, which can affect its durability [176].

It is important to note that the lower the relative humidity, the higher the rate of water evaporation.

III.4.3 Wind Speed

Wind is the movement or disturbance of air. It occurs due to the displacement of air from high-pressure zones to low-pressure zones. Wind affects the surface of concrete by accelerating convective exchanges, thereby increasing the amount of evaporated water. This evaporation can reach maximum levels if the wind speed exceeds 15 km/h.

A significant increase in the evaporation rate by approximately 300% has been observed when wind speed rises from 8 to 32 km/h [178].

It can be concluded that the evaporation rate of mixing water increases as wind speed rises. It is important to note that hot weather is not only characterized by high temperatures but also by dry and windy conditions.

III.4.4 Sunshine and precipitation

Sunshine is the measure of solar radiation received by a surface over a given period. Precipitation is the fall of water contained in the atmosphere onto the ground. These two parameters directly influence ambient temperature and relative humidity. Indeed, temperature is highly dependent on sunshine in the absence of cloud cover and rain. Solar radiation causes an increase in the temperature of stored base materials (cement, aggregate, and water) [175].

The site where construction work takes place, the formwork, and construction materials such as steel bars and masonry, as well as construction equipment (mixer, pump, tank), are heated due to their exposure to solar radiation. It is important to note that direct solar radiation also affects concrete after formwork removal, causing rapid water evaporation from its surfaces, thus accelerating the formation of cracks due to plastic shrinkage.

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In hot weather, cloud cover and rain reduce the effect of solar radiation as they absorb part of it. This results in an increase in relative humidity and a decrease in temperature, which helps limit the rate of water evaporation [176].

III.4.5 Evaporation

Evaporation occurs when the water surface is exposed to unsaturated air. Each of the parameters listed above contributes to water evaporation. Considering the interaction between these parameters, the amount of evaporated water increases. It can be concluded that evaporation is a concerning factor during concreting in hot weather.

III.5 Climatic conditions in southern Algeria (case of Laghouat province)

Algeria is the largest country in both the Maghreb and Africa. Its total area is 2.381.741 km², with 85% of it occupied by the desert. The country has a 1.200 km coastline along the Mediterranean Sea.

Algeria is characterized by a transitional climate, ranging from a humid temperate climate in the north to a desert climate in the south (Figure III. 13). It also experiences dominant rainfall in autumn with secondary precipitation in spring, irregular rainfall on daily, annual, and interannual scales, and intense summer drought [179].

To conduct an in-depth study of the climate in the Laghouat region, the meteorological services of the Laghouat province provided us with climatic data for the region over a 13-year period (2001 to 2013).

These data vary in terms of time scale (hourly, daily, monthly, seasonal, annual, etc.) and intensity (minimum, maximum, and average values). Figures.A.1, Figure.A.2, and Figure.A.3 (Annexe A) respectively illustrate the monthly variations of ambient temperature, relative humidity, wind speed, precipitation, and sunshine [180].

The results in Figure III. 14 show that the hottest month is July, with a maximum temperature reaching 42°C in the shade, followed by August, June, September, and May.

As seen in Figure III. 15, relative humidity experiences a significant decrease during the summer months, with the lowest value recorded in July at 19%. The months of November and December are characterized by relatively high humidity.

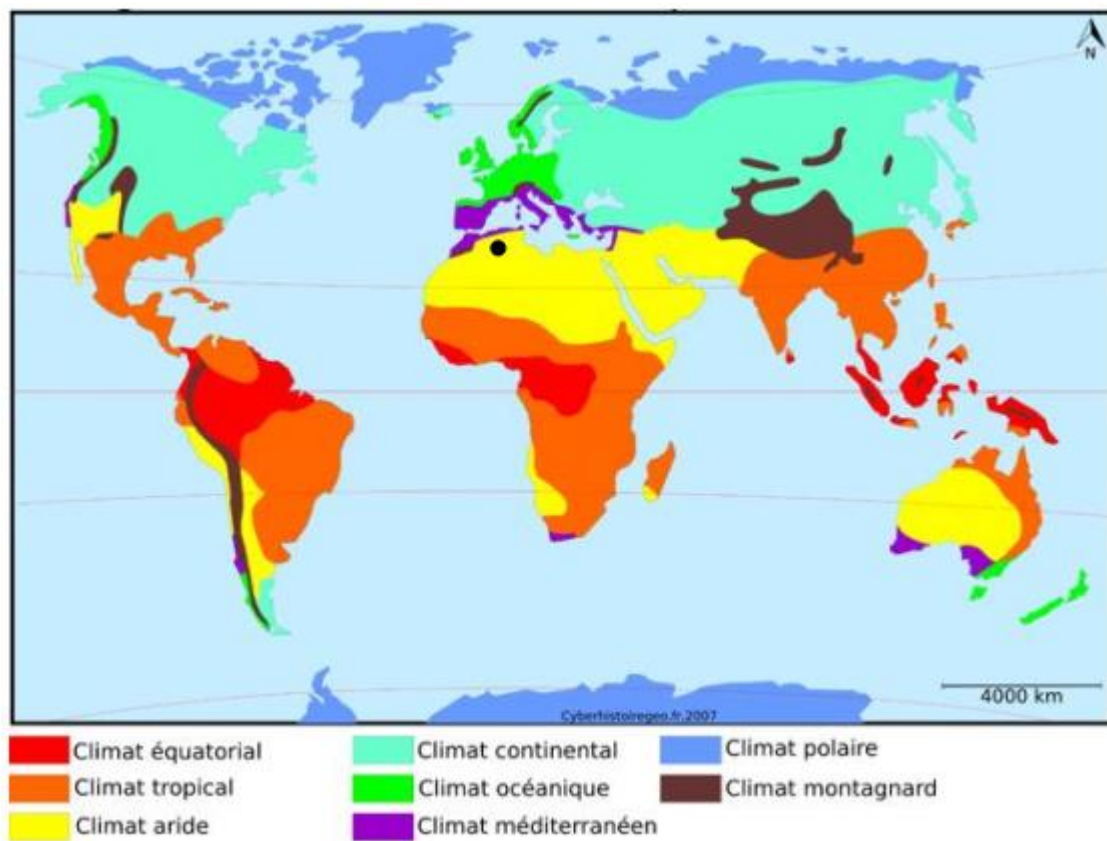


Figure III. 13 Climatological map of the world

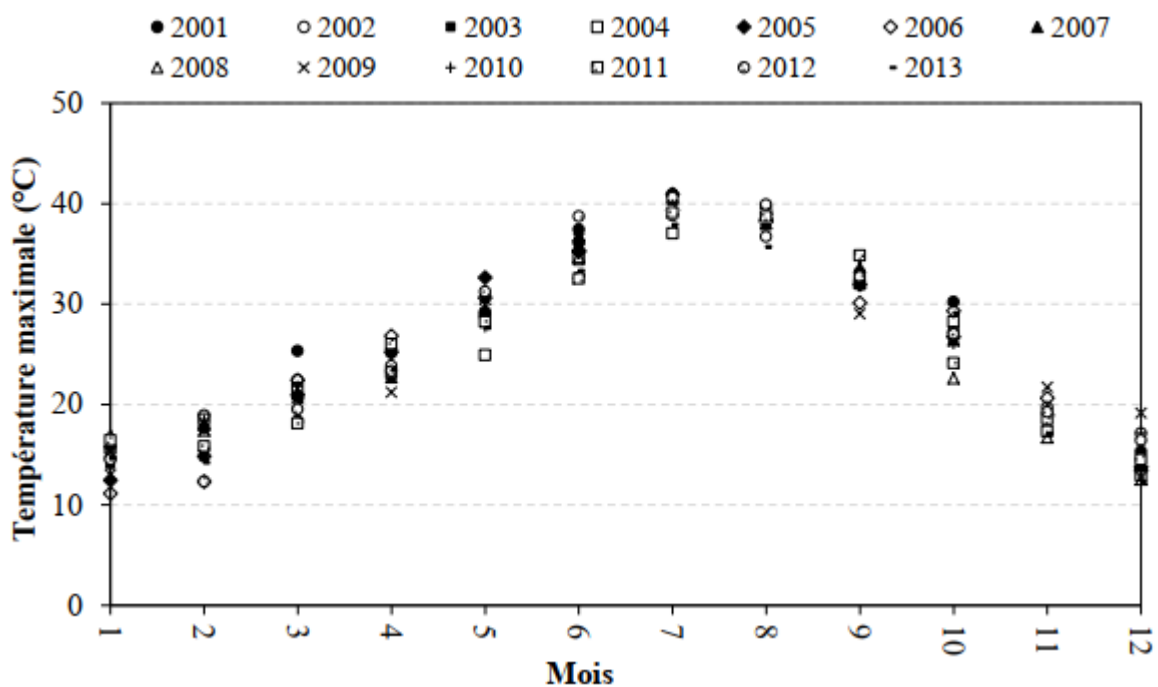


Figure III. 14 Monthly variation of maximum temperature between 2001 and 2013 [180]

Regarding wind speed, as illustrated in Figure.A.1, the Laghouat province is exposed to active winds throughout the year. The wind speed reaches its maximum values in April and May.

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The summer period in this region is characterized by almost no precipitation (Figure.A.2).

The sunniest days occur in July, with a total sunshine duration of 372 hours, followed by August (364 hours) and June (349 hours) (Figure.A.3).

These results indicate that the Laghouat region is characterized by a hot and dry summer.

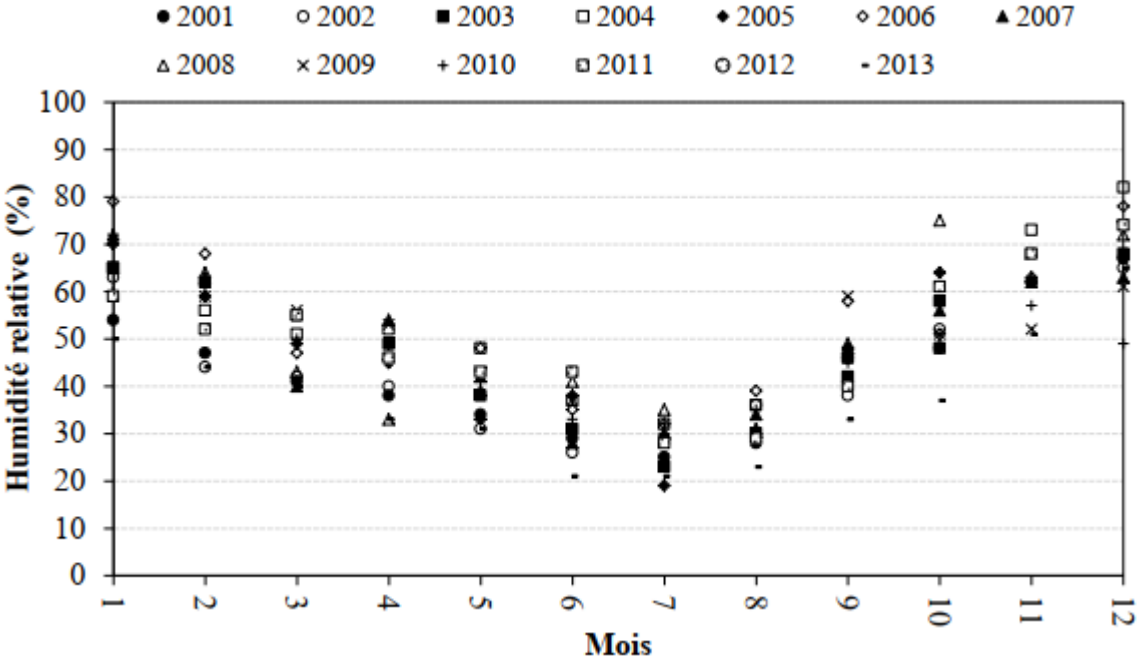


Figure III. 15 Monthly variation of humidity between 2001 and 2013

III.6 Influence of hot climate on the properties of mortars and concretes

In light of global climate change and the additional concern regarding the rising costs of renovating existing concrete structures, the performance of repair system under harsh atmospheric conditions has become an increasingly active research topic. About 50% of the repairs carried out on concrete structures end with a premature failure, as a consequence to the debonding of the repair layer due to a poor adhesion on the damaged concrete surface. The durability of the reparation depends on [181]: External exposure environment, characteristics of the substrate, characteristics of the used materials and maintenance. In light of the escalating maintenance costs, reparation must now last centuries rather than decades. However, the performance of reparation deteriorates much sooner than intended due to extreme weather conditions. To handle this problematic situation, supplementary cementitious materials (SCMs) are normally employed in combination with Portland to promote the repair properties. Some

parts of the world, such as the south of Algeria, suffer from extremely hot and arid conditions that make concrete repair susceptible to decay and inhibit its development.

III.6.1 Workability and rheological parameters

The effect of ambient temperature on flow loss was examined by Ghafoori and Diawara (Figure III. 16) [182].

Three types of self-compacting concrete (SCC) with different flow diameters (508, 635, and 711 mm) were tested and exposed to various temperatures (-0.5, 7, 14, 21, 28, 36, and 43°C).

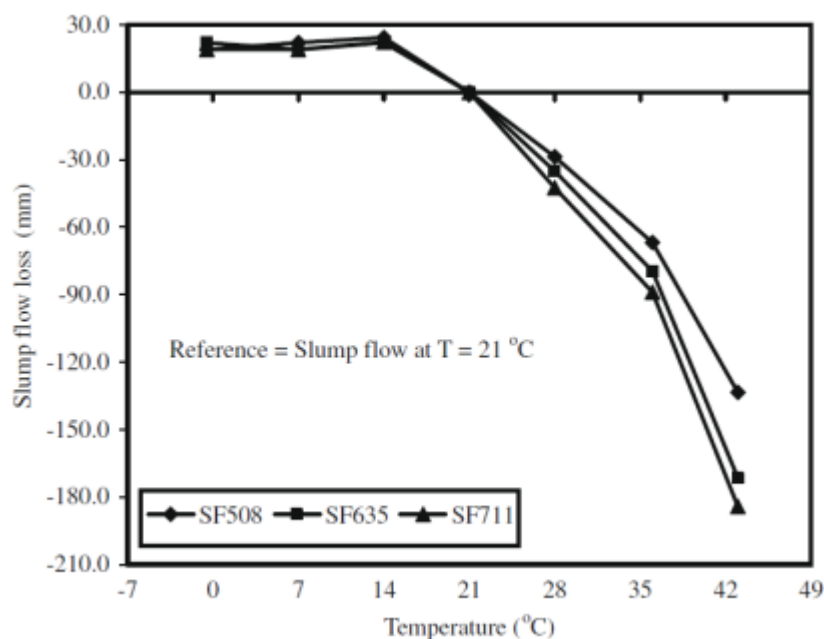


Figure III. 16 Flow loss as a function of ambient temperature [182].

According to the results in (Figure III. 16), it can be observed that the flowability remains almost stable for temperatures ranging between -0.5°C and 14°C. Beyond 14°C, the flow begins to decrease, reaching low values at 43°C.

Compared to the reference temperature of 21°C, an increase in temperature to 28°C, 36°C, and 43°C results in a flow loss of approximately 5%, 12%, and 25%, respectively.

It can be concluded that flowability is slightly affected at temperatures below 28°C, whereas beyond this threshold, a significant loss in flow is observed. This reduction impairs the self-compacting ability and limits the practical working time of self-compacting concrete.

Dada et al. [16] revealed a loss in workability of control mortar when the temperature rises from 10°C to 40 °C, the same observation is made after incorporating MP. The incorporation of MP

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showed an improvement in yield stress and plastic viscosity of all mixtures compared to those of the control mortar, regardless the temperature range (10 °C to 50 °C) (Figure III. 17).

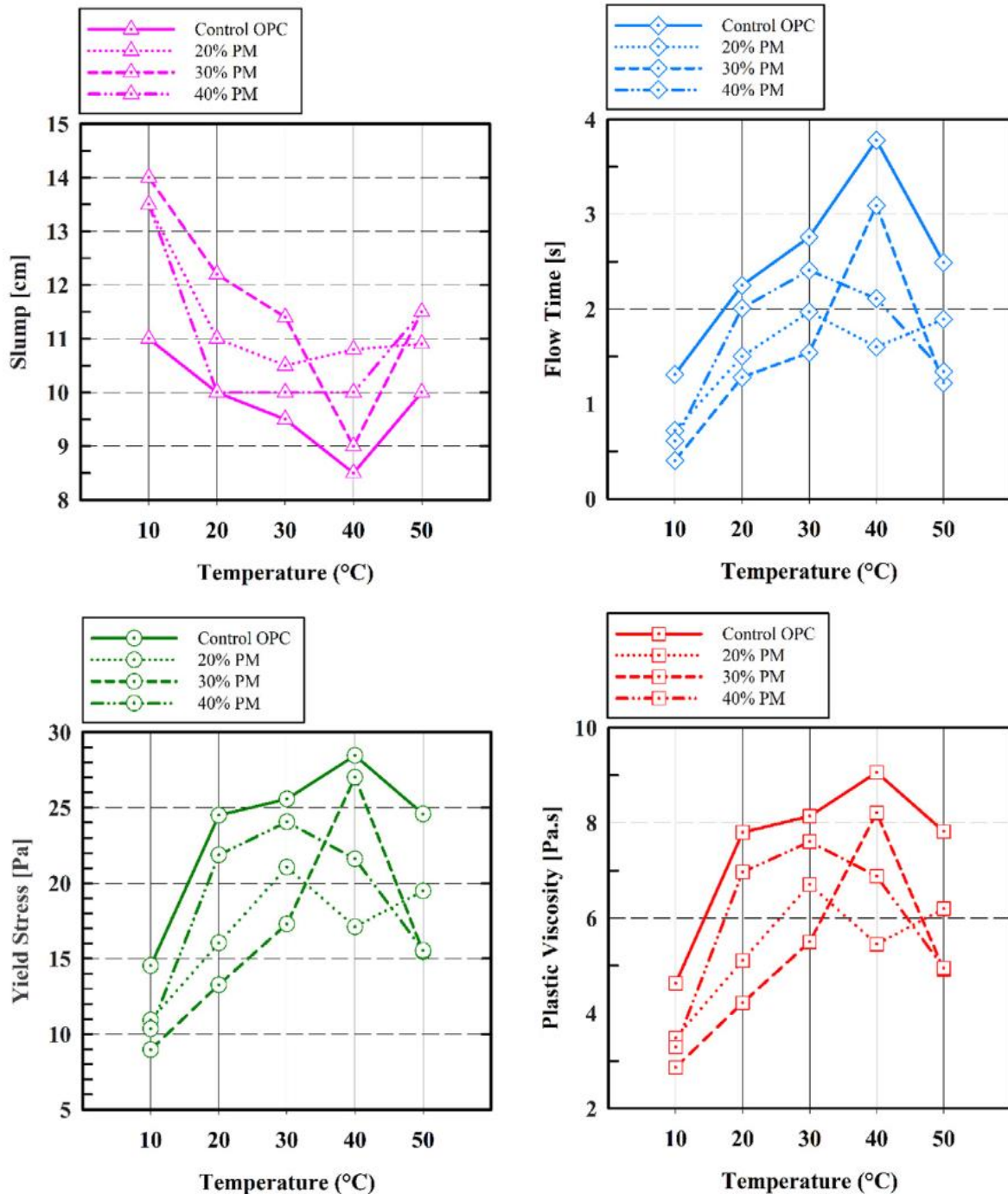


Figure III. 17 Effect of temperature on workability and rheological parameters of CEM-based marble powder [16]

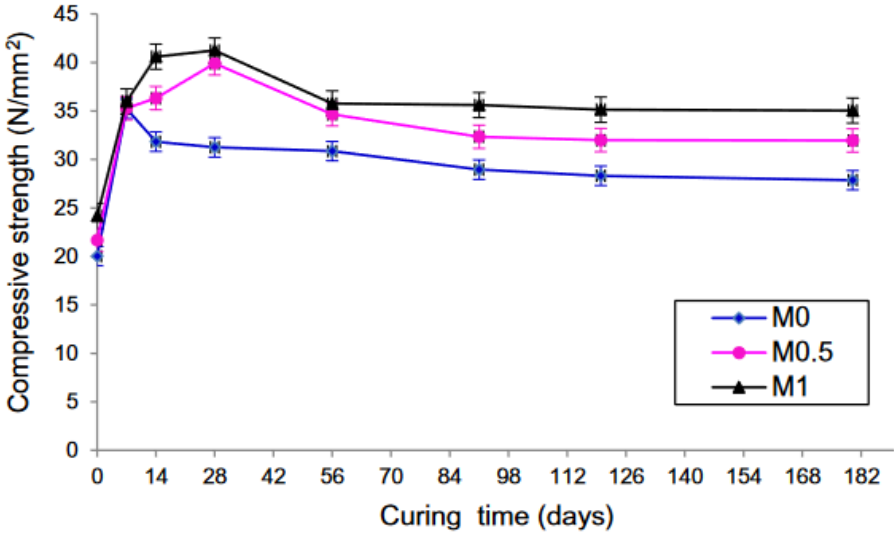
III.6.2 Compressive strength

The rate of cement hydration reaction increases as the temperature goes up. This leads to a higher early strength, but, the long-term strength of concrete will drop. This occurs due to the

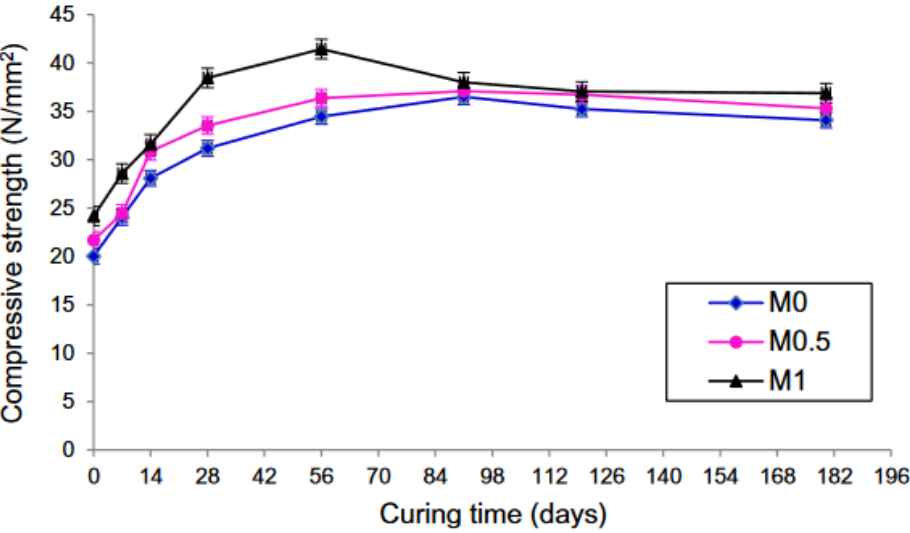
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loss of moisture and lack of concrete workability. Some researches display [183,184] that as hydration process is accelerated, the long-term strength (28 days) is condensed. This is due to the high acceleration of hydrate products at high temperature compared to the one accelerated in regular temperature ($20 \pm 5^\circ\text{C}$) [185].

Bendjillali et al. [186,187] evaluated compressive strength for mortars conserved in hot-dry conditions ($T = 45^\circ\text{C}$, $\text{HR} = 30\%$) and laboratory conditions ($T = 20 \pm 2^\circ\text{C}$, $\text{HR} = 50 \pm 5\%$).



(a)



(b)

Figure III. 18 Compressive strength evolution of mortars under (a) hot-dry conditions and (b) laboratory conditions [186].

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They concluded that mortars exposed to hot-dry conditions showed an important increase in compressive strength at 7, 14 and 28 days in all mortars compared to those conserved in laboratory conditions (Figure III. 18). After more than six months curing under hot-dry climate, the compressive strength has decreased by more than 21%. This behaviour can be explained by the fact that high temperature amplifies the hydration at the early ages. The same trend was recorded in flexural strength.

Benyahia [188] studied the influence of hot climate curing on strengths development of sisal fiber-reinforced self-compacting mortars (SFR-SCMs) incorporated natural pozzolana. The specimens that have been cured via conventional water exhibited better compressive and flexural strengths as a function of curing durations, compared to those subjected to hot climate. The optimum Portland cement replacement with natural pozzolana (NP) was at 10 wt% in both curing environments, which is probably due to the high degree of pozzolanic reaction in the NP Portland cement system (Figure III. 19). The same observation was recorded for flexural strength development.

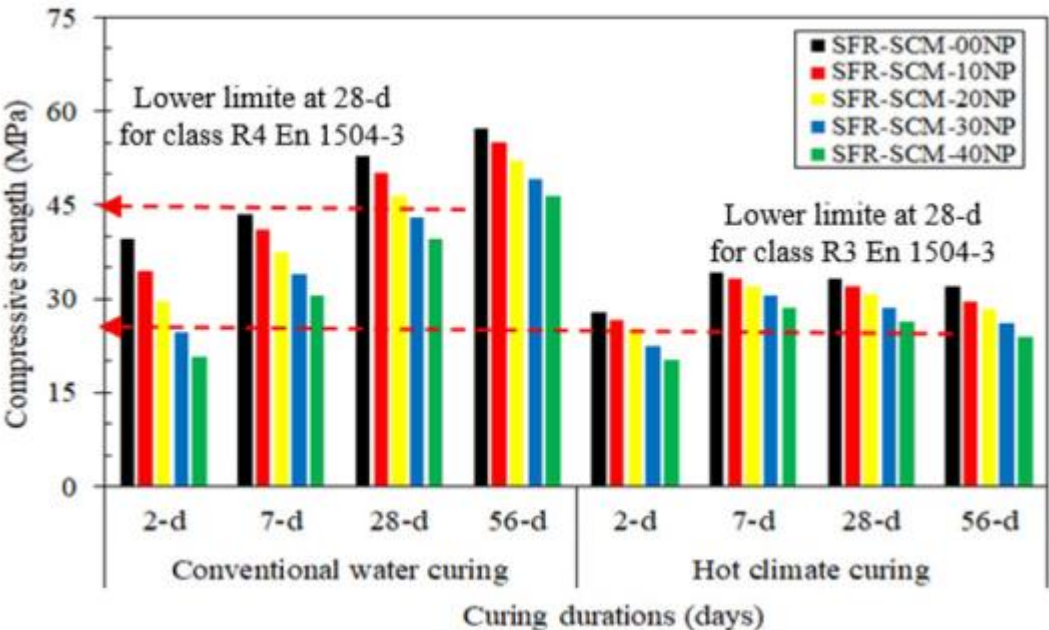


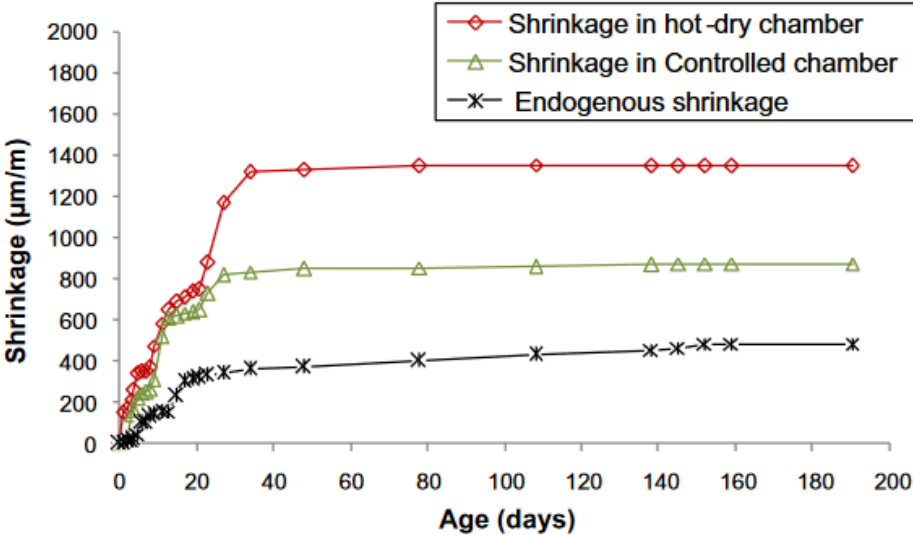
Figure III. 19 Compressive strength versus curing durations of SFR-SCMs cured in conventional water and hot climate [188].

III.6.3 Shrinkage

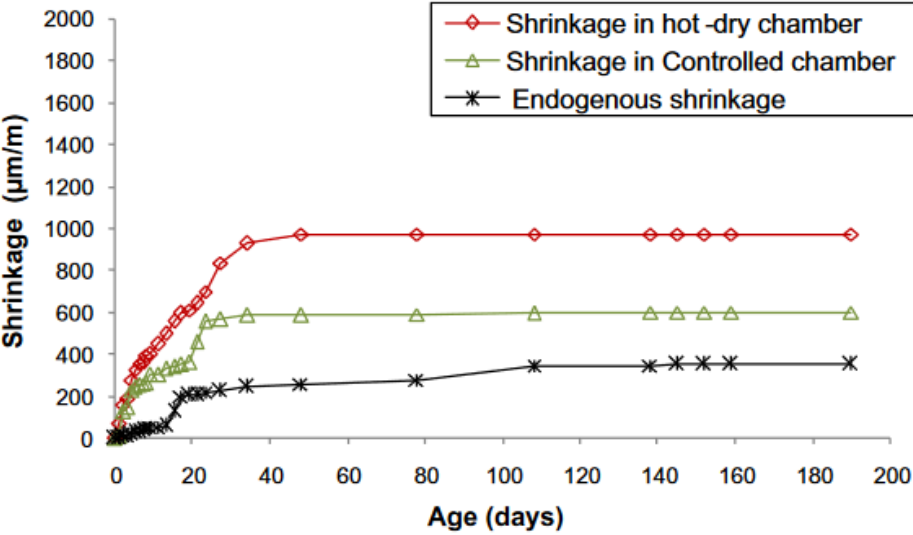
It can be seen from Figure III. 20 that the curing conditions of the hot-dry chamber have a high influence on the free shrinkage value and also on its development [186]. All mortars cured in

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hot-dry chamber reached the highest free shrinkage, which evolves rapidly and stabilises earlier due to the rapid loss of mixing water caused by high temperature (45 °C) and low humidity (30%) conditions. The curing conditions influence both the initial rate and the ultimate values of the drying shrinkage [189].



(a)



(b)

Figure III. 20 Shrinkage evolution of (a) mortar without fibre and (b) mortar with fibre in different curing conditions [186].

III.6.4 Bond strength by slant shear test

Benyahia investigated compatibility between self-compacting mortar (SCM) mixes containing recycled powder (RP) from construction and demolition waste (C&DW) (with replacement ratios of 0%, 10%, 20% and 30% RP) and parent concrete under temperatures of 200 °C, 400 °C and 600 °C for a duration of 2 h [190]. Visual inspection of all the composite samples just after their exposure in the temperature range 200–400 °C in the electric oven for a duration of 2 h showed no evidence of cracks on the external sides of the cylinders (healthy composites). The data show that the bond strength decreased by increasing heating temperatures (Figure III. 21).

The change in the adhesion strength value of the composite samples at 200 °C as compared to that of composites normally cured in water (20 ± 2 °C) is attributed to several causes, such as the decomposition of the C–S–H ($\text{CaO–SiO}_2\text{–H}_2\text{O}$) and carboaluminate hydrates ($3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{CaCO}_3\cdot 12\text{H}_2\text{O}$) and the acceleration of the hydration of the untreated cement clinker particles due to moisture evaporation at 200 °C in the recycled mortar mixtures (SCM-20RP) (Gard and Taylor 1976). The decrease of the bond strength at a temperature of 400 °C can be explained by the decomposition of portlandite which is the main hydration product of cement clinker C_3S ($3\text{CaO}\cdot\text{SiO}_2$) and C_2S ($2\text{CaO}\cdot\text{SiO}_2$) at about the temperature of 300 °C (Alarcon et al. 2005). Therefore, this replacement rate poses no risk for the development of the adhesion of repair mortar mixture (SCM-20RP) when subjected to a temperature of 200 °C and 400 °C for a duration of 2 h.

III.7 Compatibility between repair materials and substrate material

Compatibility in a repair system (Figure III. 22) is defined as a balance between the physical, chemical, electrochemical, and deformation properties of the composite (repair material/substrate). This means that, under no circumstances, should the repair be compromised by stresses due to volumetric changes, chemical processes, or electrochemical processes over time [191] (Figure III. 23).

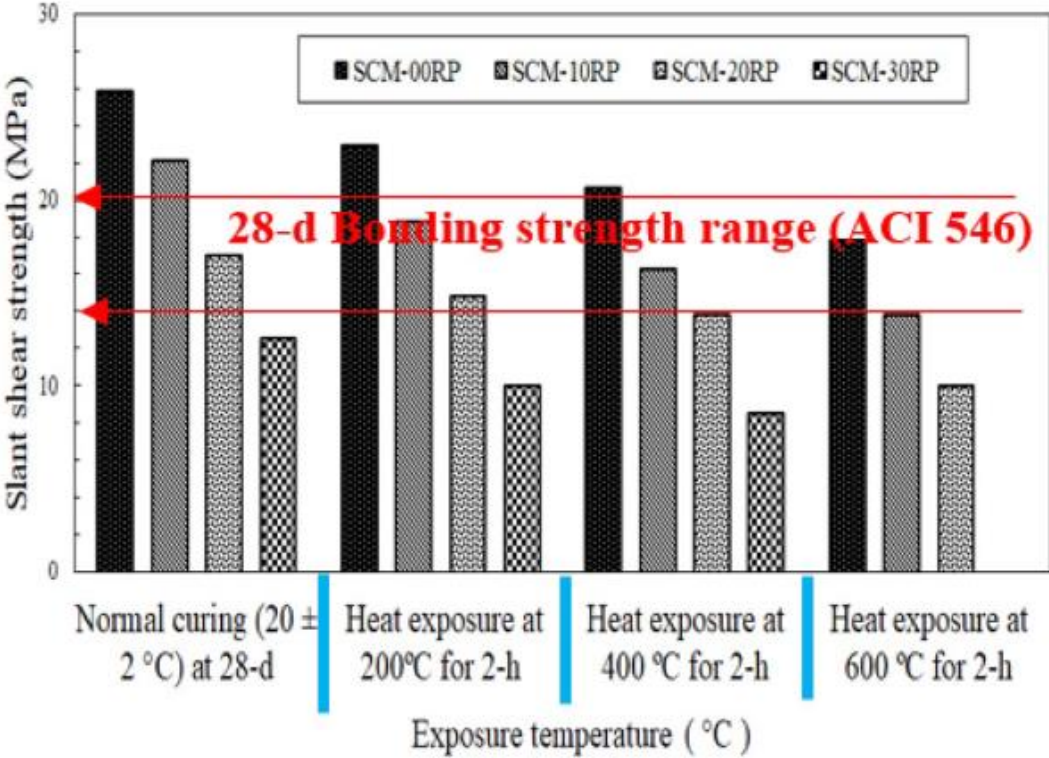


Figure III. 21 The effects of different temperatures and durations on slant shear strength [190]

Additionally, compatibility in a repair system involves the combination of properties between the repair material and the existing concrete substrate, ensuring that the combined system withstands applied stresses, maintains its structural integrity, and preserves its protective properties in a given exposure environment over a specified service life. The key aspects of compatibility include dimensional stability, chemical and electrochemical properties, and the permeability of both the repair material and the concrete substrate [192].

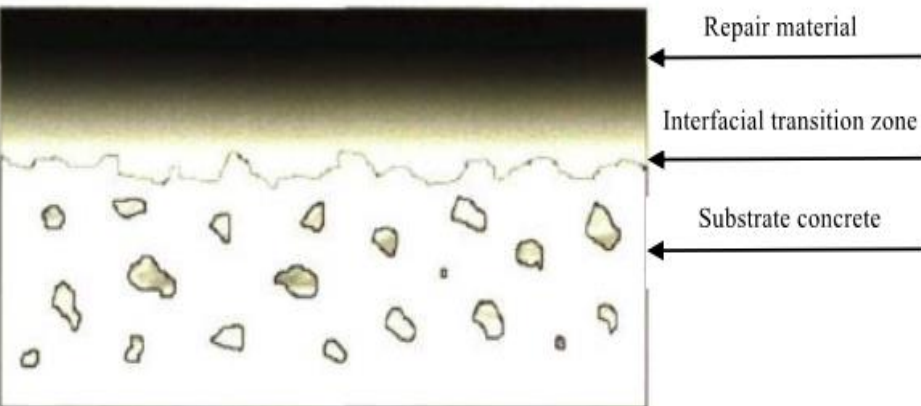


Figure III. 22 Model of a repair system [193]

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Generally, cracking of the repair material occurs after the repair work has been completed. This anomaly is typically the result of an incompatibility between the repair material and the concrete substrate. It has proven difficult to accurately determine the cause of repair degradations.

A study conducted as part of Rehabcon revealed that over 75% of the damages were caused by incorrect design (32%), poor diagnosis (12%), improper implementation (16%), and inadequate selection of the repair material (32%) (Figure III. 24).

Indeed, Table III. 2 summarizes the general requirements for repair materials to ensure structural compatibility.

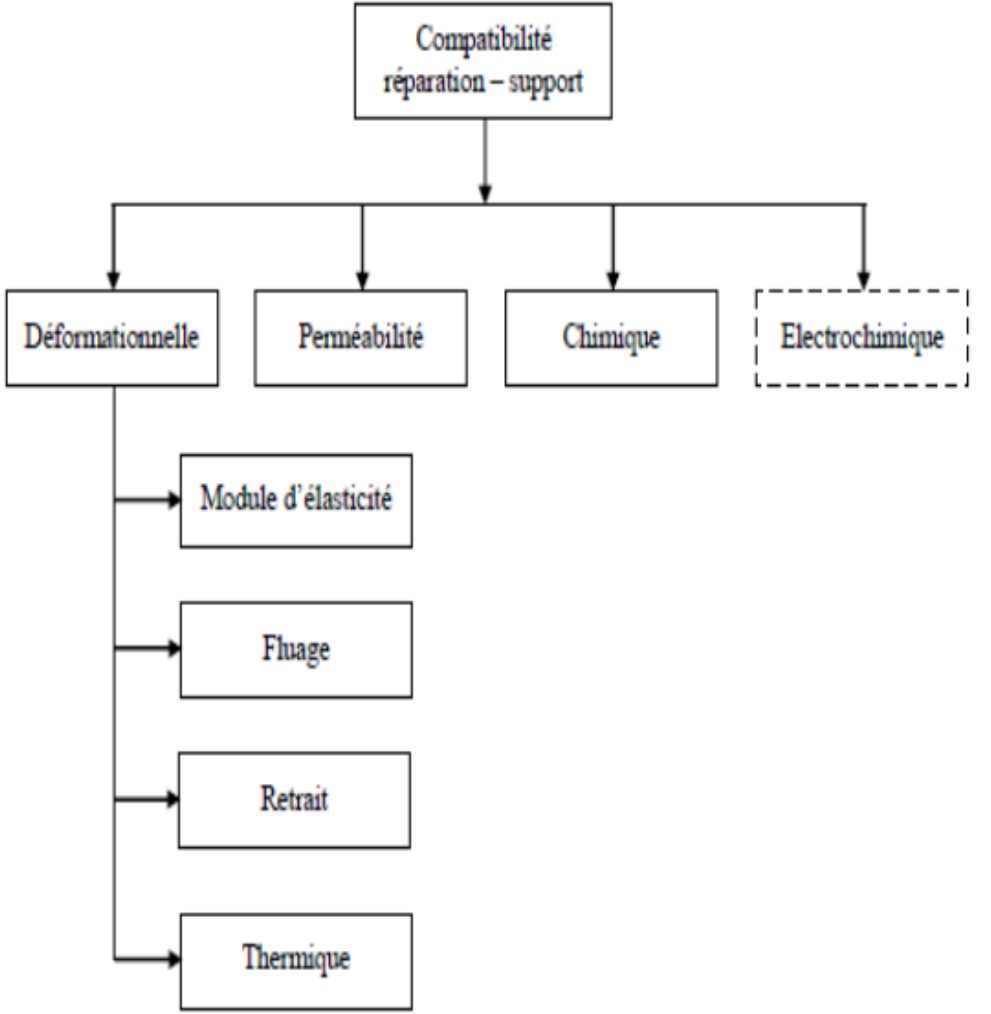


Figure III. 23 Factors affecting compatibility in a repair system [193]

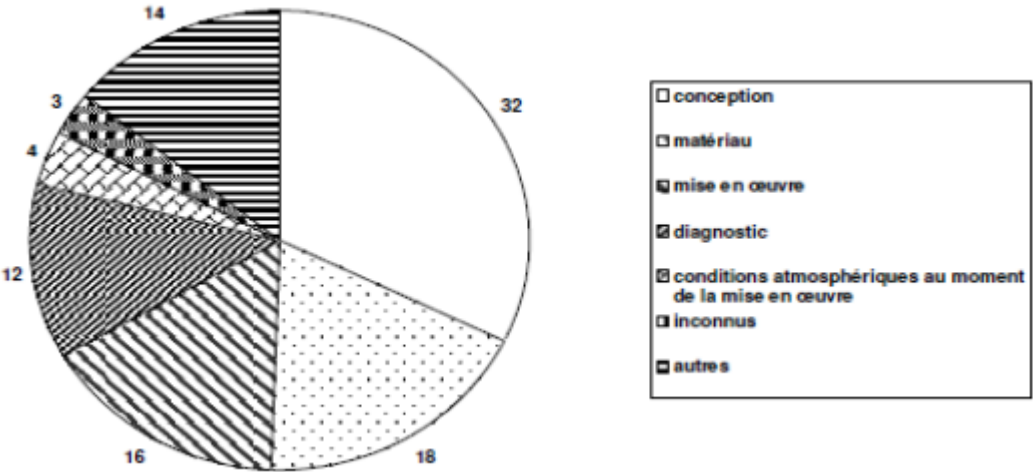


Figure III. 24 Causes of repair degradations

Table III. 2 General conditions for mechanical and dimensional compatibility [194]

Properties	Relationship between repair mortar R and substrate concrete C
Compressive strength	$R \geq C$
Modulus of elasticity	$R \geq C$
Thermal expansion coefficient	$R \geq C$
Flexural strength	$R \geq C$
Shrinkage	$R \geq C$
Adhesion	$R \geq C$

The quality of the repair system (repair mortar, existing substrate and interface transition zone) ensures its durability [195]. The performance of repair mortars can depend on various factors as rheological and mechanical behaviour [196] or on the materials compositions [197]. In this regard, numerous studies have been carried out on the workability, rheology, setting time, heat of hydration, compressive strength, flexural strength, modulus of elasticity, water absorption and shrinkage of mortars and concrete incorporated marble powder.

III.8 Adhesion strength

After examining the surface of the concrete to be repaired, we can notice the presence of a certain number of imperfections, such as cavities or even surface roughness. Since mechanical

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adhesion is closely related to macroscopic roughness, it is therefore ensured by the mechanical anchoring of the repair material, which penetrates these imperfections before hardening (Figure III. 25).

To this end, the roughness induced by the surface preparation technique (sandblasting, hydro-demolition, etc.) is an essential step for developing good mechanical adhesion of the repair mortar. However, a non-uniform microstructure and a relatively high porosity in the interfacial transition zone could be responsible for the relatively weak mechanical properties of repair systems [198].

Li et al. and Mehta [199,200] observed a significant increase in the bond strength between the repair material containing a pozzolanic addition and the concrete substrate. They concluded that this improvement is due to the roughness of the interface and the formation of C-S-H gel as a result of the pozzolanic reaction. Many studies highlight the benefits of fibres in limiting interface debonding and their contribution to the monolithic behaviour of the two concrete layers [201–203].

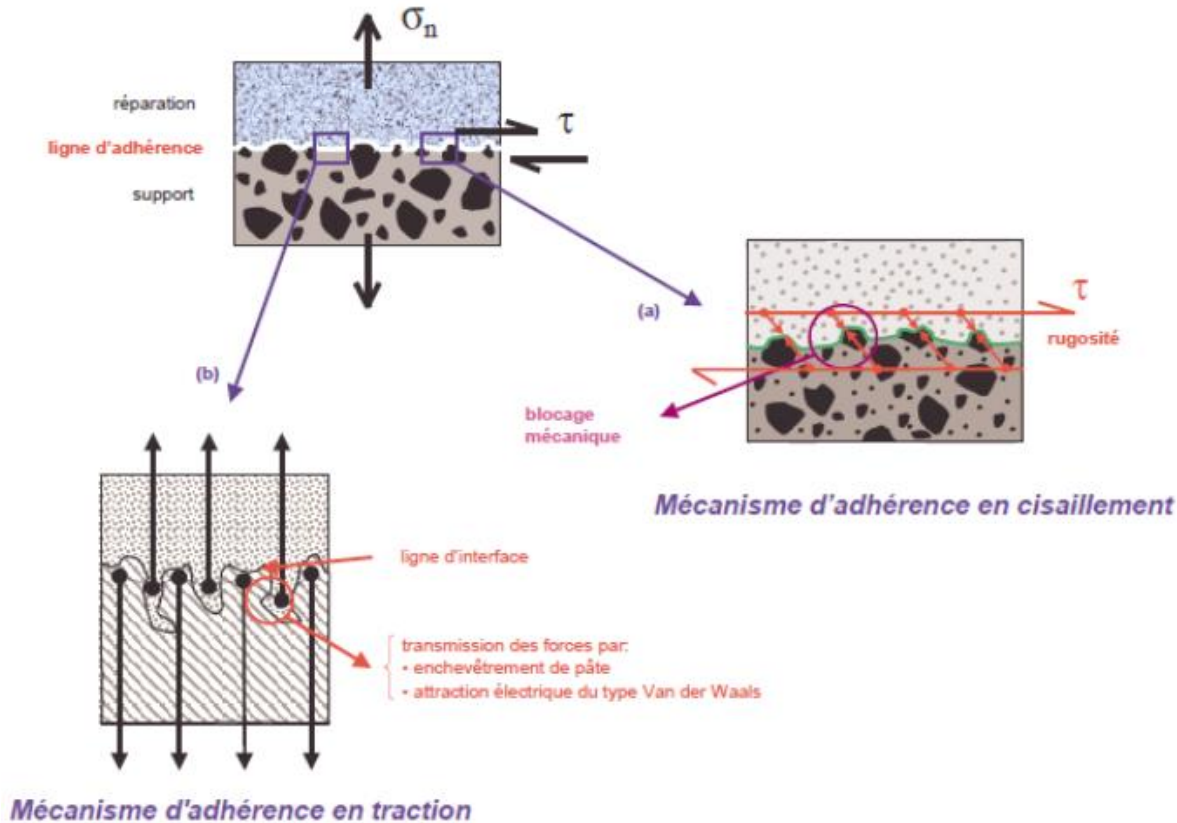


Figure III. 25 Mechanism of adhesion [204].

III.9 Different types of tests used to quantify adhesion

Several tests exist to quantify adhesion and have been developed [205] (Figure III. 26). These tests can be carried out by tension, bending, and/or direct or indirect shear.

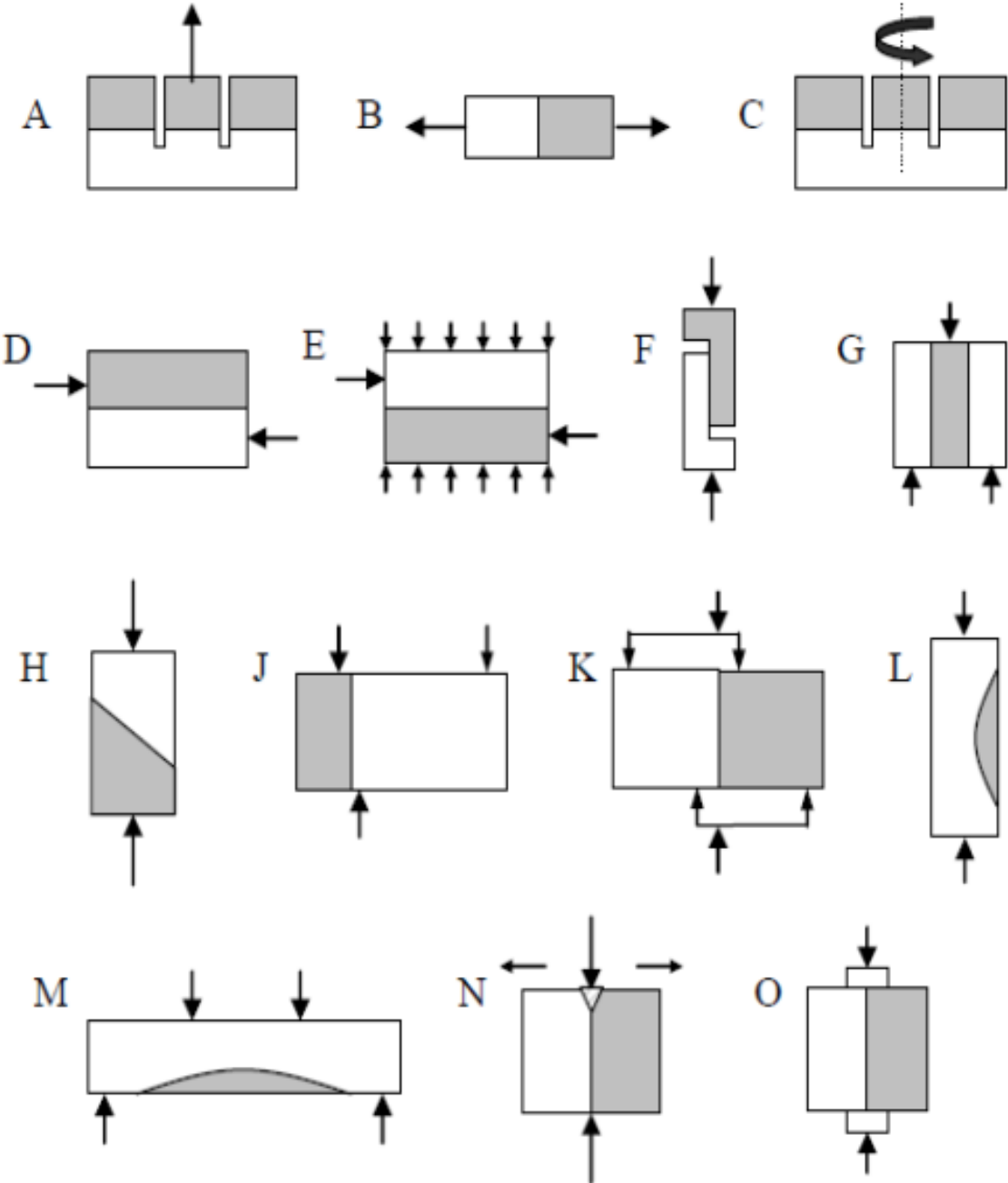


Figure III. 26 Different techniques to characterize the adhesion of repair mortars [205,206].

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Pull-off test (*Figure III. 27*) is a simple test that can be conducted both in the laboratory and on-site. A tensile force is applied using a hydraulic pump to measure the force required for the repair to fail and to determine the failure location. The failure can be cohesive within the substrate or the mortar, adhesive along the interface, or mixed (both cohesive and adhesive) (*Figure III. 28* and *Figure III. 29*). However, this device provides lower adhesion values compared to other tests that have been developed, particularly the shear test by compression (*Figure III. 26.H*).

Indeed, this test provides satisfactory values in terms of adhesion, as well as lower values in terms of the coefficient of variation (C.O.V) and standard relative error (*Figure III. 30*).

Julio et al. [207] conducted an experimental campaign to quantify the adhesion of repair mortars on concrete substrates that had undergone different surface treatments (*Figure III. 31*). Adhesion was evaluated using two distinct types of tests: the pull-off test and the slant shear test. These researchers observed the importance of surface treatment on adhesion. Moreover, the slant shear test showed significantly higher adhesion values compared to those obtained with the pull-off test (*Figure III. 32*).



Figure III. 27 Pull off device.

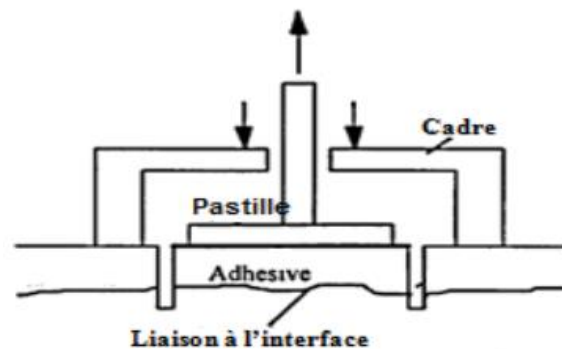


Figure III. 28 General principle of the pull-off test [208]

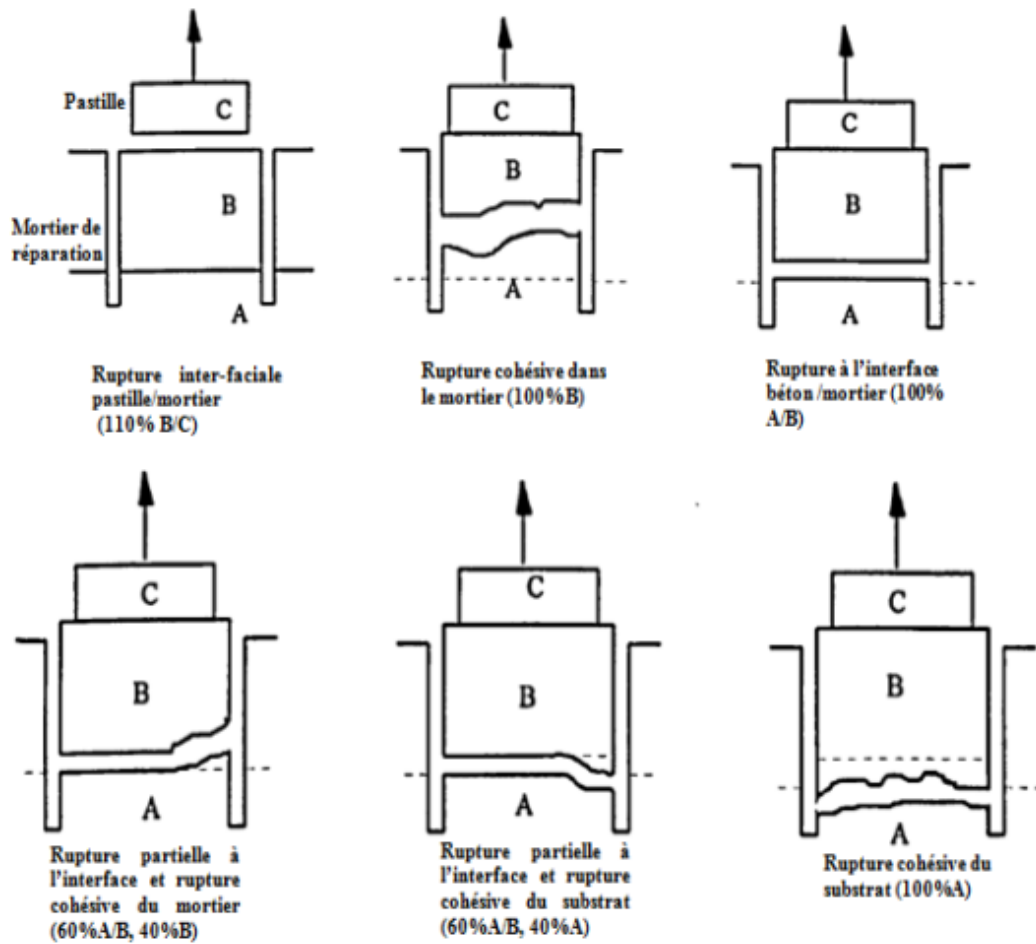


Figure III. 29 Possible failure modes of the concrete/repair mortar composite in the pull-off test [208].

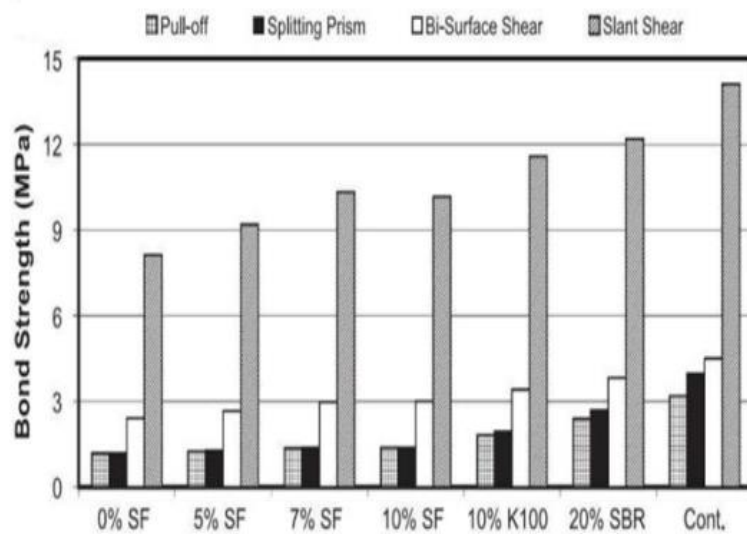


Figure III. 30 Adhesion measured using the methods in Figure 3.7 for a low surface roughness of the substrate

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Figure III. 31 Surface treatment methods [207].

Table III. 3 Results of the pull-off test [207]

Considered situations	Substrate treatment	Adhesion (MPa)
1	Without treatment	--
2	Metallic brushing	1.92
3	Partially perforated	1.47
4	Partially perforated and pre-wetted	1.02
5	Sandblasting	2.65

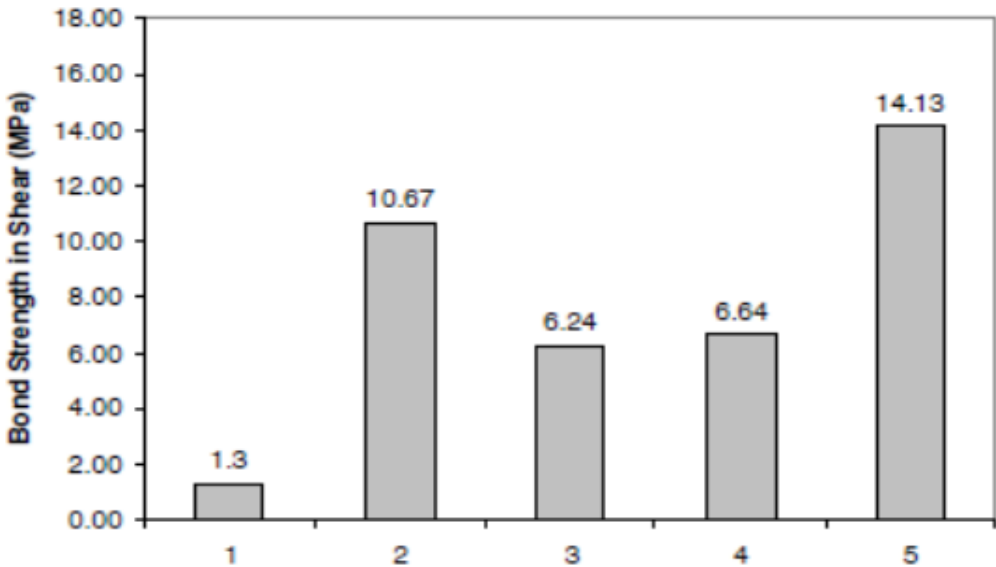


Figure III. 32 slant shear test results [207].

To evaluate adhesion performance, Anagnostopoulos and Anagnostopoulos [209] conducted a four-point bending test on a composite brick-mortar specimen, as shown in (Figure III. 33).

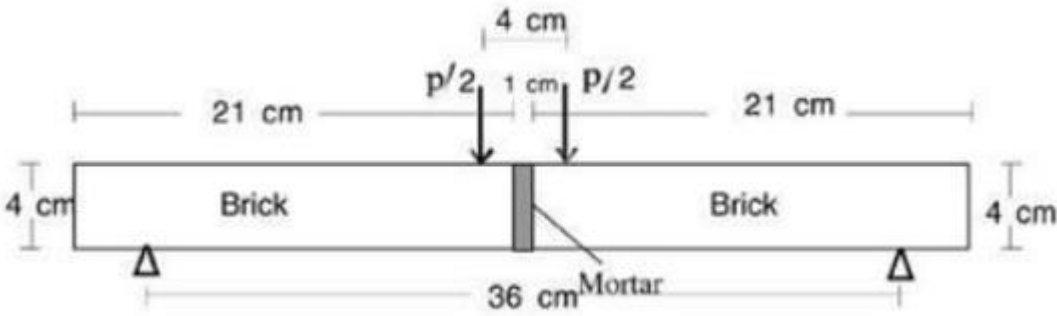


Figure III. 33 Four-point bending adhesion test [209].

On the other hand, Qiao et al. [210] conducted two types of tests: the pull-off adhesion test and the bending test, as shown in (Figure III. 34). The pull-off test was performed to measure adhesion strength under direct tension, while the bending test is an indirect flexural test.

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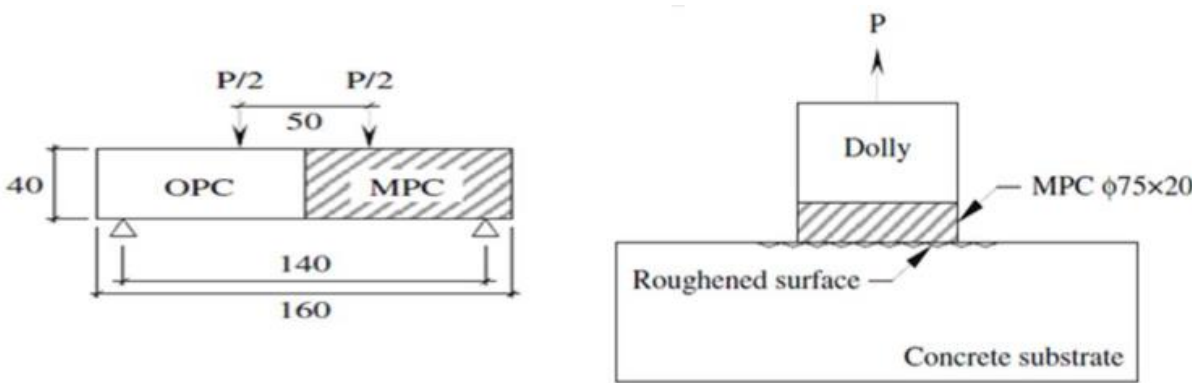
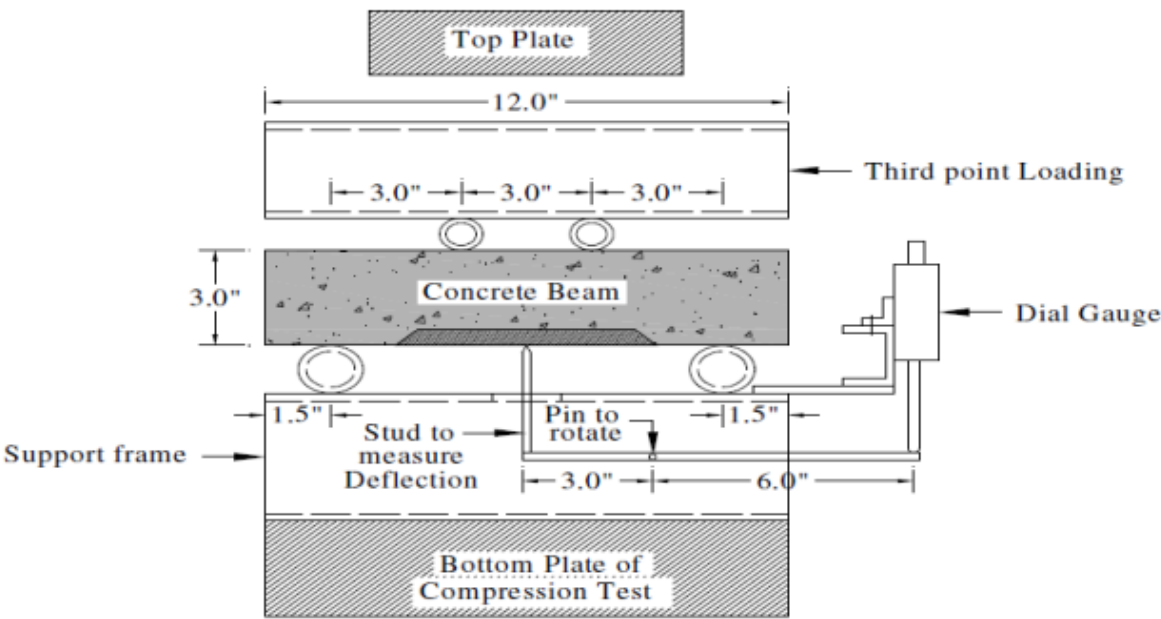


Figure III. 34 a) Adhesion strength by flexural test and b) Adhesion strength by traction (unit in mm) [210]

Czarneck et al. [211] fabricated five (05) non-reinforced beams. After curing for 28 days, the researchers prepared the substrates of each beam by sandblasting. The beam repairs were carried out after 7 days.

For comparison purposes, the repaired beams were stored in three curing environments: dry air, humidity, and an alternating cycle of dry air and humidity. The objective was to assess the compatibility or incompatibility of the repair materials with the substrate.

The beams were subjected to four-point loading (Figure III. 35) in accordance with ASTM C78. The failure modes (compatible or incompatible) were classified as illustrated in (Figure III. 36).



(a) Skeletal View

Figure III. 35 Measurement of beam deflection

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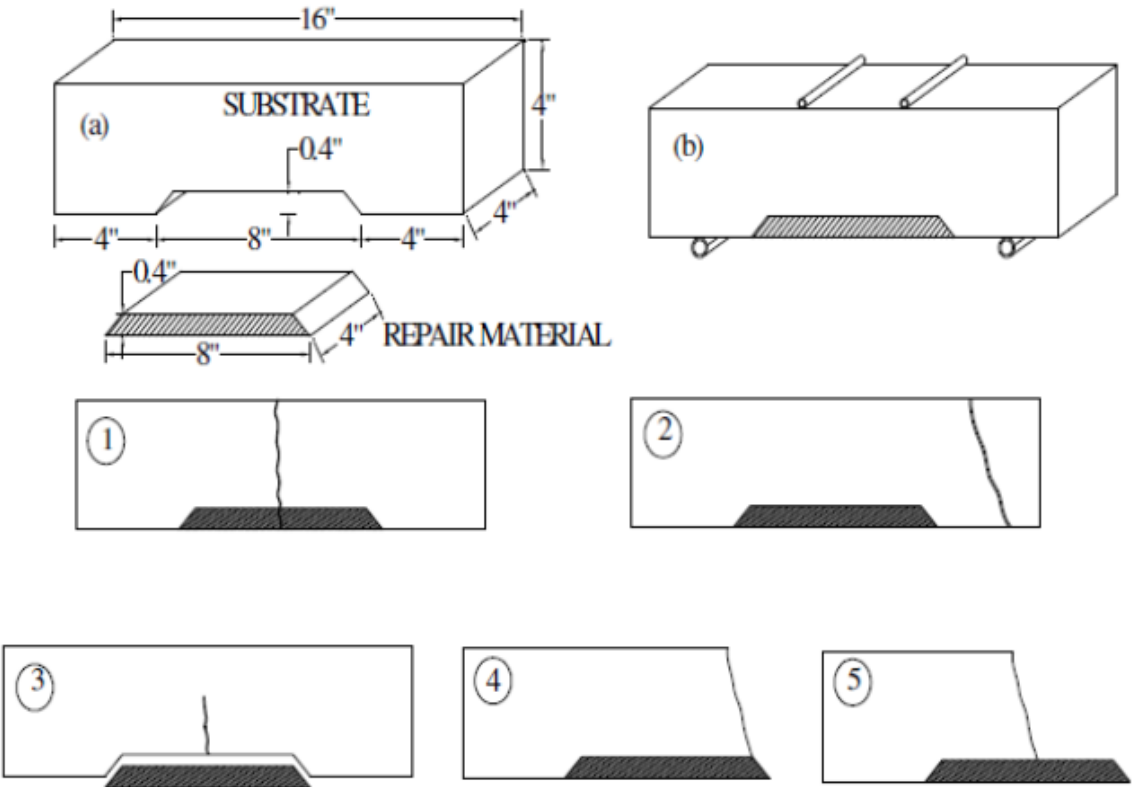


Figure III. 36 Evaluation of compatibility through four-point loading test [211]: 1,2 - Compatibility; 3,4,5 - Incompatibility.

Furthermore, Habel [212] reported that a repaired element (concrete beam) subjected to bending can exhibit three failure modes: either cracking that extends through the entire thickness of the repair, delamination at the interface (loss of monolithic behaviour), or failure of the concrete in compression. However, when the repair is subjected to negative bending moments and cracks, this can lead to either conventional bending failure or bending failure due to interface rupture.

III.10 Conclusion

This chapter demonstrated that incorporating marble powder as a partial replacement for cement positively influences the properties of concrete and mortar, enhancing workability, compressive strength, and durability. However, the effects of hot climate conditions pose challenges, including accelerated setting time and increased risk of cracking due to rapid moisture loss.

Furthermore, we have seen that the behaviour of a repaired element is strongly influenced by the adhesion between the repair material and its substrate. Therefore, the designer of a repair must always take certain factors into account to achieve a durable repair that behaves monolithically with the existing element. The main factors can be summarized as follows :

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- The required properties in the fresh state for a durable repair are primarily related to the workability of the repair material. For this reason, self-compacting mortars are preferred in repair works.
- The aspects of compatibility include the dimensional stability, chemical, electrochemical, and permeability properties of the repair material and the concrete substrate. The most important parameter is the dimensional compatibility of the repair material with the substrate concrete, which depends on the composition of the repair material used, such as the dosage and type of binder, the water-to-binder ratio (W/B), the nature and dosage of fibres, the use of mineral additions... etc.

Chapter IV

Materials and experimental program

IV.1 Introduction

The main objective of our thesis work is to experimentally evaluate the effect of marble powder (MP) as a substitute for cement on the performance of self-compacting fibre-reinforced repair mortars (SCFRM), which are intended for the repair of concrete structures. Previously, an optimisation of fibre dosage in terms of fresh and hardened states was assessed. Five mortars were prepared, containing 0.02%, 0.03%, 0.06%, 0.09% and 0.12% compared to control mortar (CM0) without fibres to choose the optimal dosage as a second control mortar (CM1). Then MP was incorporated at different dosages (10%, 15%, 20%, 25% and 30%) and compared to control mortar with 0.06% of PPF (CM1).

The effect of marble powder on the properties of self-compacting fibre-reinforced mortar mixes was experimentally studied at both states: fresh state (slump flow, flow time, yield stress, plastic viscosity and fresh density) and hardened state (compressive strength, flexural strength, dry density, shrinkage, dynamic modulus of elasticity, thermal conductivity, water absorption, sorptivity, mercury intrusion porosity and adhesion). Adhesion strength was evaluated through three methods (bonding tensile test, slant shear test and three-point flexural test) in two different real climates (standard climate $T = 20 \pm 2^\circ\text{C}$ and $\text{RH} = 25 \pm 5\%$; hot-dry climate $T = 40 \pm 5^\circ\text{C}$, $\text{RH} = 10 \pm 5\%$).

IV.2 Characteristics of the used materials

The characteristics of used materials in the formulations of self-compacting repair mortars, substrate mortar and concrete are presented below.

IV.2.1 Cement

Portland cements used are of type CEM II/A-L 52.5 N and CEM I 42.5 R according to the standard EN197-1 [213]. Physical and mechanical characteristics of both cements are presented in *Table IV. 1*. CEM II/A-L 52.5 N cement (C1) was used in the formulation of self-compacting repair mortars, CEM I 42.5 R (C2) cement was used in the formulation of substrate mortar and concrete.

chemical analysis is given in *Table IV. 2*. To analyse morphology, particle size and shape microscopic images (MEB) are presented in *Figure IV. 4*. While *Table IV. 5* and *Figure IV. 2* presents particle size distribution by a laser scattering technique. EDX analysis is given in *Figure IV. 3*.

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Table IV. 1 Physical and mechanical characteristics of the used cements and marble powder.

	CEM II/A-L 52.5 N	CEM I 42.5 R	MP
Bulk density (kg/m³)	1020	1100	
Specific density (kg/m³)	3030	3040	2.62
Fineness (g/cm²)	3850	3500	5000
Consistency (%)	26.4	25.8	--
Setting time (min)	150-250 min	150 – 190 min	--
Flexural strength (MPa)	5.8	3.5	--
Compressive strength (MPa)	≥ 52.5	42.5 – 52.5	--

Table IV. 2 Chemical analysis of both cements and marble powder.

Elements (%)	CEM I 42.5	CEM II/A-L 52.5	Marble Powder
CaO	64.48	62.20	54.15
SiO ₂	19.79	19.25	--
Al ₂ O ₃	4.51	4.85	--
K ₂ O	0.66	0.68	0.04
CO ₂	2.41	4.36	43.44
Fe ₂ O ₃	3.17	3.14	0.06
SO ₃	2.32	2.59	0.03
P ₂ O ₅	0.18	0.14	0.01
TiO ₂	0.24	--	--
Na ₂ O	0.10	--	--
MgO	3.10	--	--
SrO	0.05	--	--

Table IV. 3 Mineralogical component of cement

Constituents	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
C1 (%)	62	21	01	07
C2 (%)	61	28	02	06

Table IV. 4 Mineralogical component of marble powder

Constituents	Dolomite	Calcite	Quartz
MP (%)	20	79	--

IV.2.2 Marble powder

A commercial Marble powder (MP) is used in this study. In order to obtain a fineness near to that of cement, MP was grind for 2 hours using Micro Deval apparatus with a quantity of balls of 1 kg and 1.5 kg of MP. Then, it was sieved in a mean-particle diameter sieve of 80 μm (Figure IV. 1).



Figure IV. 1 Marble powder

Table IV. 5 Particle size.

	Cement 1	Marble powder
d(10) (µm)	2.327	1.966
d(50) (µm)	13.678	9.476
d(90) (µm)	40.295	35.708

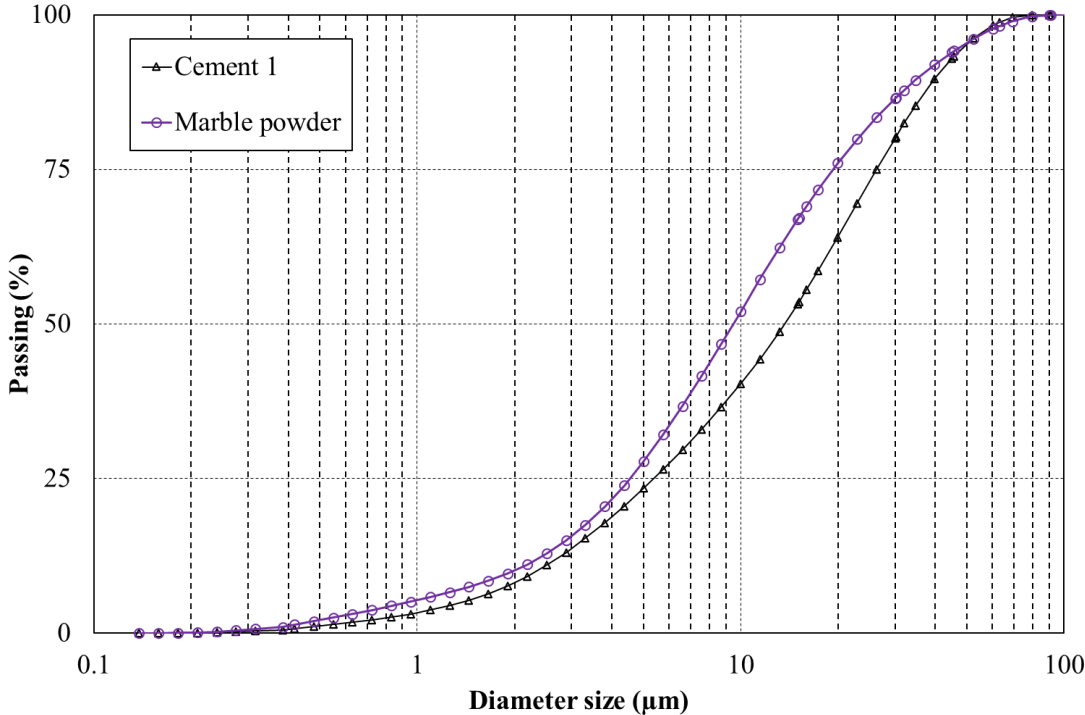
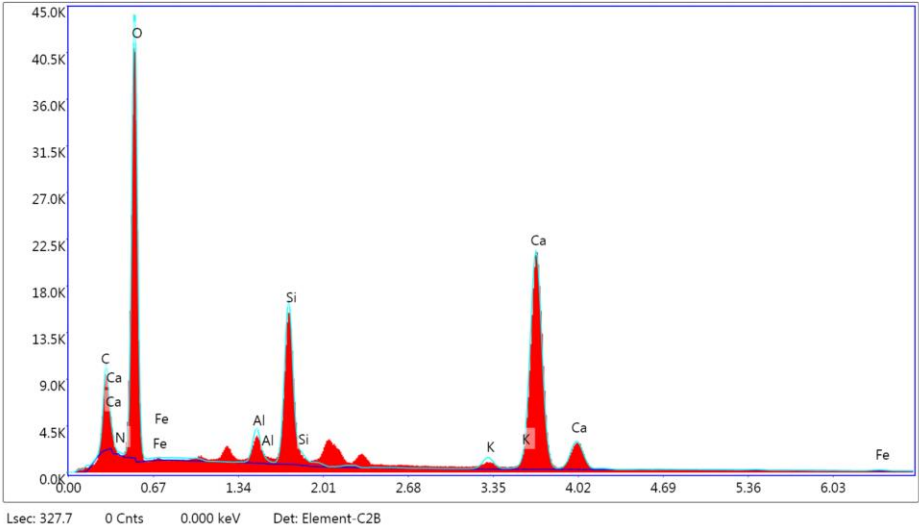
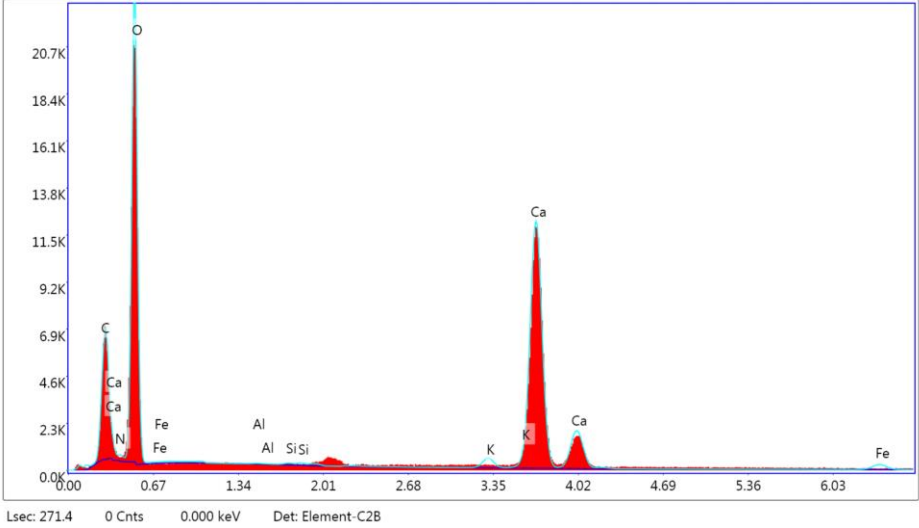


Figure IV. 2 Laser particle size distribution of cement 1 and marble powder.

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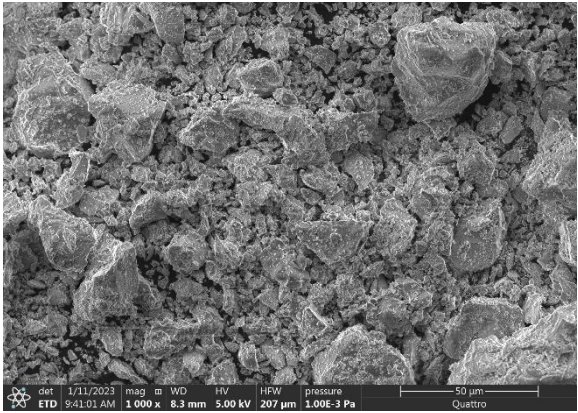
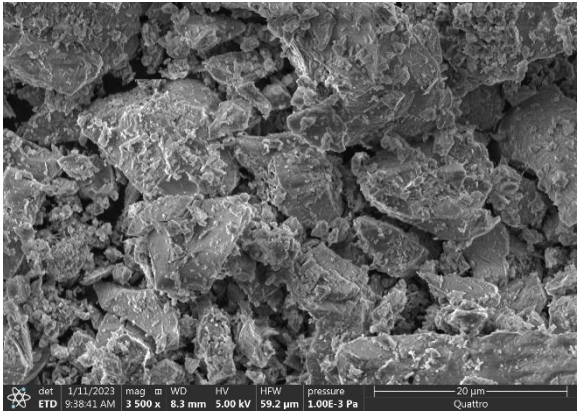


(a)

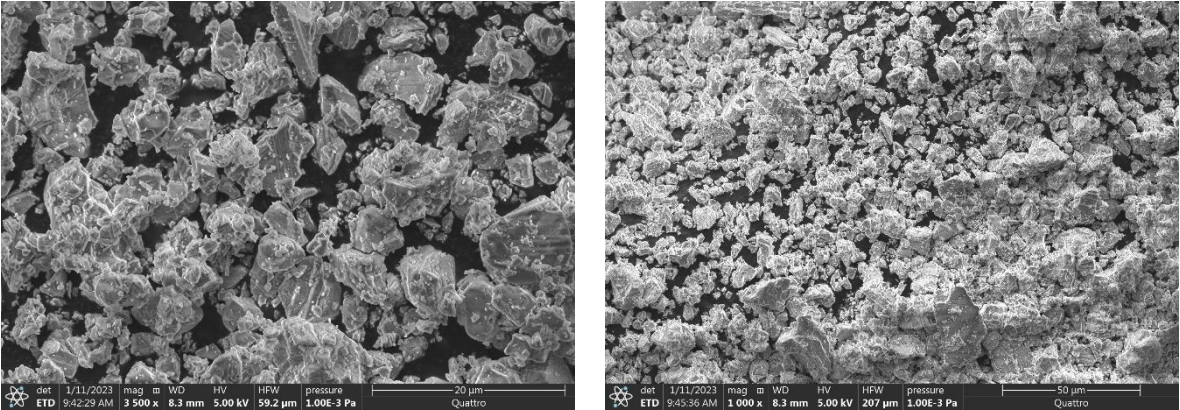


(b)

Figure IV. 3 EDX analysis of (a) cement 1 and (b) marble powder



(a)



(b)
Figure IV. 4 Microscopic images (MEB) of: (a) cement 1 and (b) marble powder.

IV.2.3 Polypropylene fibres

Fibres used in this investigation are polypropylene obtained from the market. *Table IV. 6* presents its characteristics. *Figure IV. 5* shows microscopic images (MEB).

Table IV. 6 Polypropylene fibre characteristics

Surface	Length	Diameter	Specific density	Specific surface	Tensile strength	Elasticity modulus
	(mm)	(µm)	(kg/m ³)	(m ² /kg)	(N/mm ²)	(N/mm ²)
Smooth	12	32	905	135	260	± 3.500 - 3.900

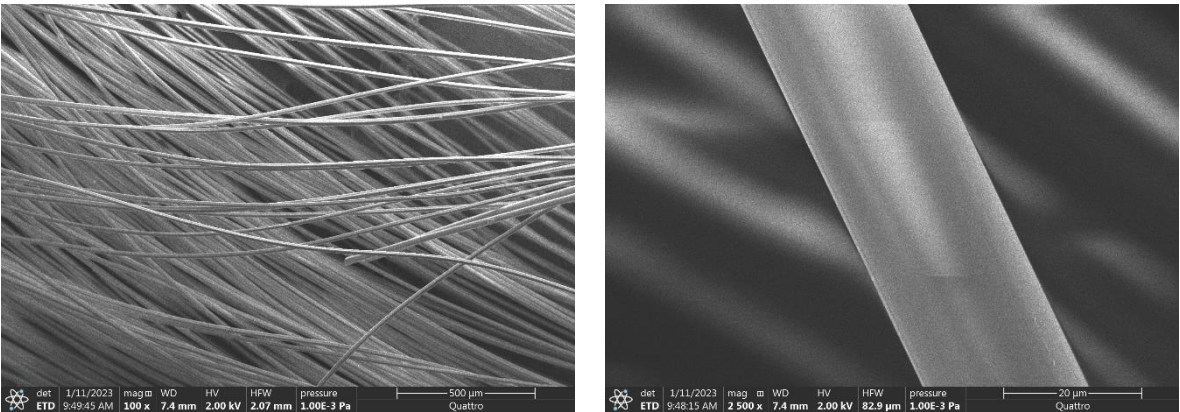


Figure IV. 5 Microscopic images (MEB) of polypropylene fibres.

IV.2.4 Fine aggregate

River sand from Oued Mzi in Laghouat city is used as fine aggregate in the formulation of both repair and substrate material. Its particle size ranges from 0 to 5 mm after passing in a sieve of 0/5 mm according to the standard NF EN 933-1 [214]. Its physical properties are given in *Table IV. 7*. Granulometric distribution is presented. Sand (S1) and sand (S2) are used in the formulation of repair and substrate materials, respectively.

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Table IV. 7 Physical properties of aggregates.

Properties of aggregates	Standard	Aggregates		
		Sand (S1)	Sand (S2)	Gravel (G)
		0/5	0/5	8/15
Bulk density (g/cm³)	NF P 18-555	1.64	1.59	1.37
Specific density (g/cm³)		2.60	2.52	2.3
Absorption coefficient (%)		0.58	0.28	0.82
Sand equivalent (%)	NF P18-554	92.5	83.86	--
Fineness modulus	NF EN 933-1	2.41	1.9	--

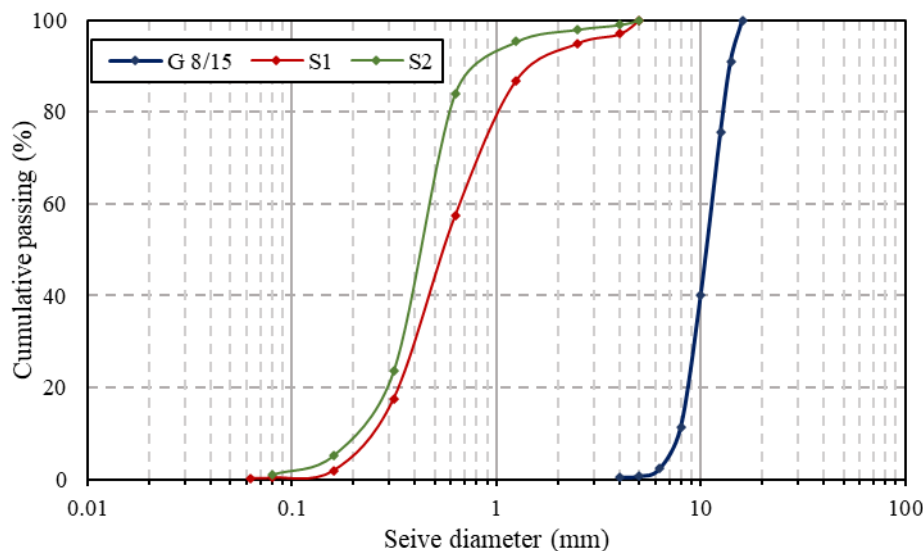


Figure IV. 6 Particle-size distribution of fine and coarse aggregates

IV.2.5 Coarse aggregate

Coarse aggregate (gravel) used for the production of substrate concrete is natural limestone, obtained from a local quarry in Laghouat city (Ouazzane crushing station). Its largest diameter is 15 mm. Its physical properties are given in Table IV. 7. Particle size distribution is presented in Figure IV. 6.

IV.2.6 Superplasticizer

A high water-reducer superplasticizer is used as admixture, manufactured by Granitex company under the name MEDAFLOW 30. It is based on modified polycarboxylate ether. Its normal usage range, as specified by the technical data sheet, is 0.5% to 2% (in dry extract) of the cement

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weight. It is in liquid form with yellow colour and 30% dry extract. It has a density of 1.07 and pH between 6 and 6.5. Technical data sheet is given in the annexe.

MEDAFLOW 30 is compatible with all cements, it contributes to a considerable improvement in the properties of mortars in the fresh state. Thanks to its properties, it leads to reduce water-cement ratio, considerable improvement in fluidity, very good workability, prevention of segregation and facilitate concrete placement.

IV.2.7 Mixing water

The used mixing water is a potable tap water of the laboratory of Laghouat University.

IV.3 Mix proportions

The experimental study comprises three sections. The first part consists on the preparation of substrate mortar and concrete. In the second part, formulation and characterisation of self-compacting repair mortars incorporating polypropylene, marble powder in the fresh and hard state are conducted.

In the third part, we focused on studying adhesion and compatibility characteristics between self-compacting repair mortars and substrate material to obtain more detailed data on the overall performance of the developed repair mortars.

IV.3.1 Substrate concrete

Dreux-Gorisse method is chosen as the experimental method for concrete formulation. It allows for determining the optimal quantities of materials (water (W), cement (C2), gravel (G), sand (S)) needed to compact one cubic meter of concrete according to the loads. The prepared substrate concrete is commonly used in Algeria. Mix proportions are indicated in Table IV. 8.

Table IV. 8 Mix proportions of substrate concrete (kg/m³)

CEM I 42.5	G	S	W	W/C	Slump (cm)	σ_c (Mpa)
416	990.7	610.5	207.7	0.5	9	30±2

Ordinary concrete mixing process is carried out as follows:

- ✓ Sand (S2) and gravel are mixed for 1 min,
- ✓ Cement (C2) is added and mixed for 1 min,
- ✓ Introducing mixing water then mixed for 1 min and 30 sec,

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- ✓ The mixture is relaxed for 30 sec,
- ✓ After that, remixing for another 1 min.

Workability of fresh concrete was characterised by slump in Abram's cone according to the standard **EN 12350-2** [215]. We fill the Abram's cone in three layers, each layer is compacted with 25 blows using a metal bar with a 16 mm of diameter. Then, we level the concrete surface and lift the mould vertically and carefully. Finally, the slump is measured immediately afterward.

IV.3.2 Substrate mortar

Substrate mortar is a standard mortar constituted with cement, fine aggregate and mixing water using a 5-litter mortar mixer. Mixtures are prepared as follows:

- ✓ Fix sand to cement ratio (C/S) equal to 1/3, with C = 450 g.
- ✓ Vary the W/C ratio to achieve a desirable workability, without the use of admixture.

Its composition is given in Table IV. 9.

Table IV. 9 Mix proportions of substrate mortar (g/cm³)

CEM I 42.5	S	W	W/C	C/S	Flow time (s)	Rc (Mpa)
450	1350	247.5	0.55	1/3	5	40±2

Standard mortar was prepared following these steps:

- ✓ Sand (S2) and cement (C2) were mixed together for 1 min,
- ✓ Water was introduced and mixed for 1 min,
- ✓ Then, the mix was relaxed for 30 sec while scraping the sides and the bottom of the bowl.
- ✓ After that, we keep mixing for 1 min at low speed and 30 sec at high speed.

Workability of fresh standard mortar is characterised by Maniabilimeter B (Figure IV. 7) according to the standard **NFP18-452** [216].



Figure IV. 7 Maniabilimeter B

IV.3.3 Repair mortar

For the preparation of repair mortars, we have adopted the formulation of self-compacting mortar based on the formulation proposed by the Japanese researcher OKAMURA [55]. With adjusting the sand/mortar ratio, water/binder ratio and superplasticizer/binder ratio. These modifications were experimentally evaluated by slump flow and flow time tests. Furthermore, mortars must meet two essential requirements: high fluidity and sufficient resistance to both static and dynamic segregation.

All mixes were prepared according to the requirements of the European Federation for Specialist Construction Chemicals and Concrete Systems **EFNARC 2005** [61]. Three series of self-compacting mortars were prepared and detailed Table IV. 10 with Sp variable, and Table IV. 11 Sp constant. Polypropylene fibres were added relative to the total volume. Marble powder was used to replace cement at different dosages.

Table IV. 10 Composition of mixtures (kg/m³).

Series	Mixtures	Cement (kg)	MP (kg)	Sand (kg)	Fibre (%)	W/B	Sp (%)	SF (cm)
Series 1 (PPF)	CM0	872.51	00	1170	0.00	0.3	0.6	25
	F2				0.02		0.5	27
	F3				0.03		0.6	26
	F6(CM1)				0.06		0.6	26
	F9				0.09		0.6	27
	F12				0.12		0.6	25
Series 2 (PPF+MP)	F6+10MP	785.26	87.25	1170	0.06	0.3	0.6	27
	F6+15MP	741.64	130.88				0.6	27
	F6+20MP	698.01	174.50				0.5	27
	F6+25MP	654.39	218.13				0.4	26
	F6+30MP	620.76	261.75				0.4	25.5

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Table IV. 11 mix proportions of repair mortars (kg/m³).

Series	Mixtures	Cement (kg)	MP (kg)	Sand (kg)	Fibre (%)	W/B	Sp (%)
Series 1 (PPF)	CM0	872.51	00	1170	0.00	0.3	0.6
	F2				0.02		
	F3				0.03		
	F6(CM1)				0.06		
	F9				0.09		
	F12				0.12		
Series 2 (PPF+MP)	F6+10MP	785.26	87.25	1170	0.06	0.3	0.6
	F6+15MP	741.64	130.88				
	F6+20MP	698.01	174.50				
	F6+25MP	654.39	218.13				
	F6+30MP	620.76	261.75				

Mixing sequence adopted for self-compacting mixtures is as follows, a 5-litter mortar mixer was used.

- ✓ Mix cement (C1) and sand (S1) for 1 min to homogenize the mixture,
- ✓ Add the first amount of water (Water 1 = 70% Water) and mixed for 1 min,
- ✓ Mix for 1 min the remaining mixing water (Water 2 = 30% Water) with the superplasticizer.
- ✓ Relax the mix for 30 sec,
- ✓ Add polypropylene fibres slowly for 30 sec,
- ✓ Mix the mixture for 30 sec at slow speed then, for 30 sec at high speed.

IV.4 Samples preparations and test methods

IV.4.1 Repair mortar

IV.4.1.1 Rheological characterisation

Understanding the rheological properties and workability of concrete, mortar, and cement paste provides an indication of their quality; since they are generally non-Newtonian fluids, whose rheological properties play a crucial role in their flow behaviour [217]. The rheological behaviour of cementitious materials depends on numerous internal factors (type of cement, hydration rate, water to cement ratio W/C, dosage of mineral additives or admixtures) besides to external factors (temperature, mixing method, transport) [218].

➤ Slump flow

slump flow test using mini cone in truncated shape (height of 60 mm, upper and lower diameter of 70 mm and 100 mm) Figure IV. 8. Bleeding, segregation and fibre's agglomeration were also

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visually checked. The diameter value was measured in both directions and their average is defined as slump-flow diameter. The desired flowability in accordance with the EFNARC specifications is (24 - 26 cm) [61].

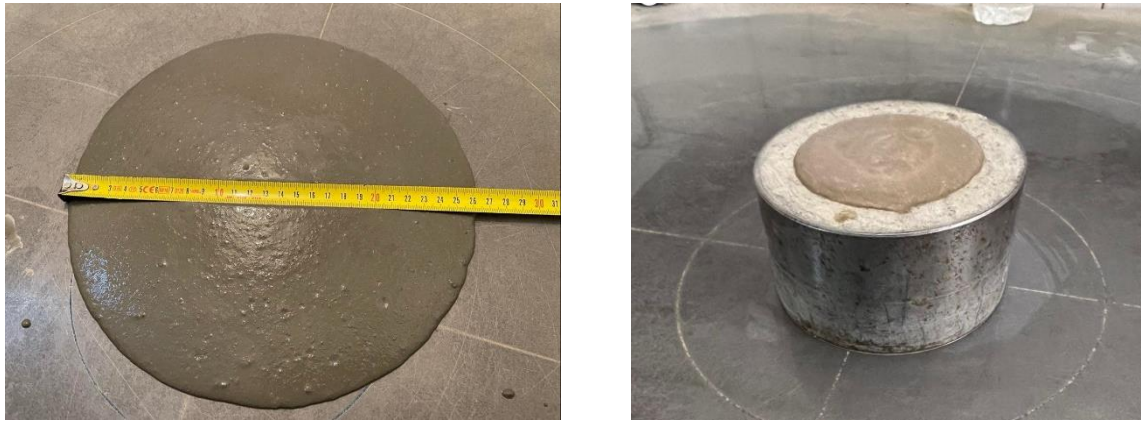


Figure IV. 8 Slump flow test.

➤ Flow time

Mini V-funnel can be used to evaluate the flowability by measuring the flow time Figure IV. 9. Flow time is the period needed for a specific volume to pass through a narrow opening. It could be related to the plastic viscosity. The allowable range given by EFNARC specifications is (7-11s) [61].



Figure IV. 9 V-funnel test.

➤ Yield stress and plastic viscosity

The rheological tests were performed using a coaxial rheometer. The description of the apparatus is showed in Figure IV. 10. An agitator controlled by the "Watch and Control" software, a cylindrical container with a diameter of 10 cm and a height of 15 cm and a steel vane are the principal components of the apparatus. The steel vane welded parallel to the axis

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of the container with an X-shaped ($d = 5 \text{ cm}$, $h = 10 \text{ cm}$) *Figure IV. 10*. In our study the rheometer developed by Soualhi et al. [219] was used in order to determine the rheological properties of self-compacting repair mortar. With a very low coefficient of variation (0.15 Pa for the yield stress and 0.015 Pa·s for the plastic viscosity), thus confirming the precision and reproducibility of the tests. The assisted software allows the record of couples of rotations corresponding to the required rotational speeds *Figure IV. 11*. The rheological test consists on placing the steel vane inside the rheometer container. Fresh mortar is filled in the container, the vane centred and dipped in the middle of the mortar until uppermost level of the mortar then rotated at different speeds to measure the torque necessary to maintain rotation. A maximum rotation speed is applied at the beginning of the test to eliminate thixotropy. At every second, the software records the torque (M) corresponding to the imposed speed (Ω). The data of a rheometer test are given as a linear function linking torque and rotational speed following the equation below.

$$M = M_0 + k \Omega \quad (\text{Equation IV. 1})$$

With:

- M (N.m) is the total torque applied to the concrete.
- M_0 (N.m) is the torque at the origin.
- k (N.m.s) is a linear regression coefficient.
- Ω (rad/s) is the angular torque speed of the vane

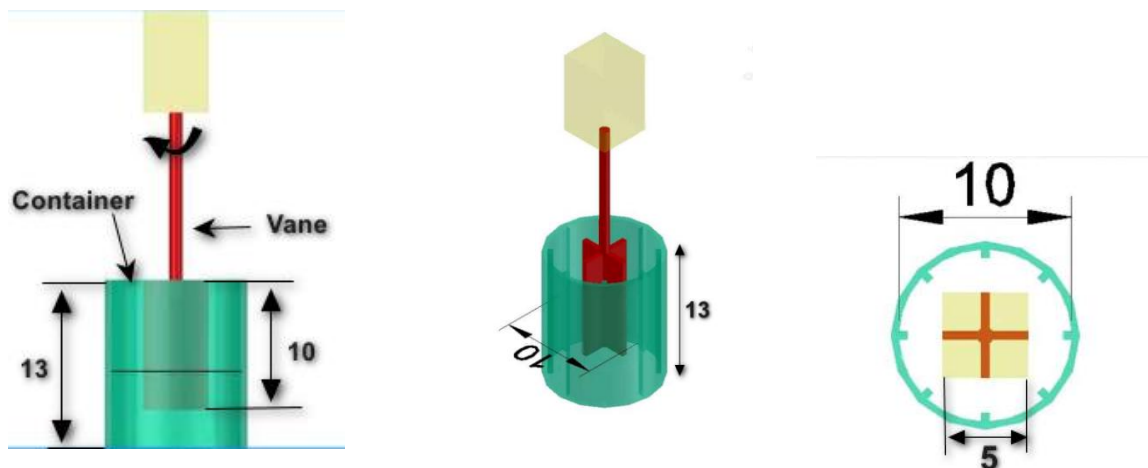


Figure IV. 10 Rheometer components

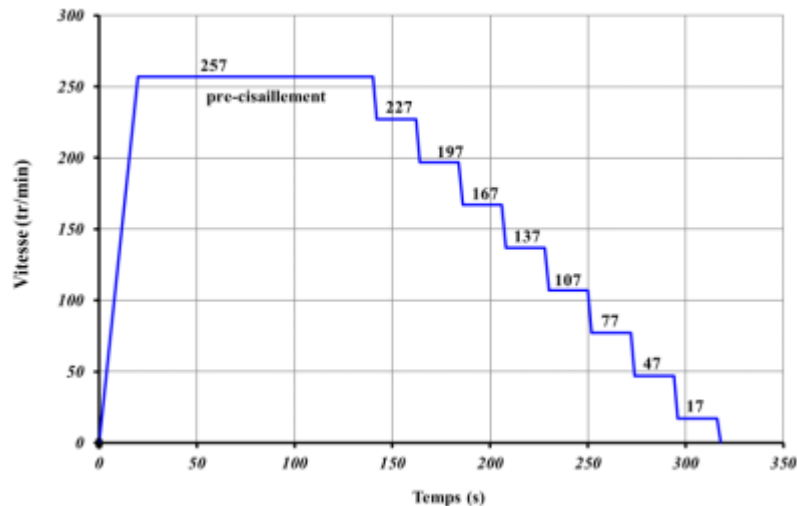


Figure IV. 11 Imposed speed profile.

In order to determine rheological parameters (τ_0) and (μ), formulas developed by Estellé et al. can be used to study the evolution of the shear stress (τ) as a function of the shear rate ($\dot{\gamma}$) of the pair (Mi- Ω i) through rheologic measurements [219–221]. The Bingham model equation was used to describe the rheological behaviour of mortar.

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (\text{Equation IV. 2})$$

With:

- τ (Pa) is the shear stress.
- τ_0 (Pa) is the yield stress.
- μ (Pa.s) is the plastic viscosity.
- $\dot{\gamma}$ (1/s) is the shear rate.

The rheological test is carried out as following:

- ✓ First, measurement of the empty torque (M_{empty}) which corresponds to the torques measured to maintain the imposed speeds when the container was empty.
- ✓ Then, the container is filled with the fresh mortar and the vane is immersed until the uppermost level of the mortar,
- ✓ After that, measurement of the total torques (M_{total}) which corresponds to the imposed torques to maintain the imposed speeds when the container is filled with mortar,
- ✓ Finally, determining the final torques (M) which presents the difference between the total and the empty torques for each speed level:

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$$M = M_{\text{total}} - M_{\text{vide}} \quad (\text{Equation IV. 3})$$

➤ Fresh bulk density

Fresh bulk density is evaluated according to the standard NP EN 12350-6 [222] using a recipient of 1L. First, we measure the mass of the empty recipient (m_1). Then, measurement of the filled recipient (m_2) (Figure IV. 12). The apparent density of the fresh repair mortar is determined as the ratio of its mass to the volume it occupies.

$$\rho = \frac{m_2 - m_1}{v} \quad (\text{Equation IV. 4})$$

With

- ρ is the apparent density of the fresh mortar (kg/m^3),
- m_1 is the mass of the empty recipient (kg),
- m_2 is the mass of the recipient filled with mortar (kg)
- v is the volume of the recipient (m^3).



Figure IV. 12 Fresh bulk density

IV.4.1.2 Compressive and Flexural strength

According to EN 12190 [223] standard for repair mortars, compressive and flexural strength are measured after 3, 7, 28 and 90 days of age on prismatic specimens ($40 \times 40 \times 160$) mm^3 conserved in saturated-lime water ($T = 20 \pm 2^\circ\text{C}$, $\text{RH} = 100\%$). Flexural strength is the average of three specimens, while the compressive strength is the average of the six resulting halves from the flexural strength test.

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Flexural test is conducted using test beam under third-point loading (Figure IV. 13), with a charging speed of 5 kN/s. Flexural strength σ_f is calculated as follows:

$$\sigma_f = \frac{3FL}{2b^3} \quad (\text{Equation IV. 5})$$

With

- σ_f is the flexural strength (N/mm²),
- F is the maximum load (N),
- L is the distance between the two supports on the tension surface of the beam (L = 100 mm),
- B is the width of the beam (b = 40 mm),

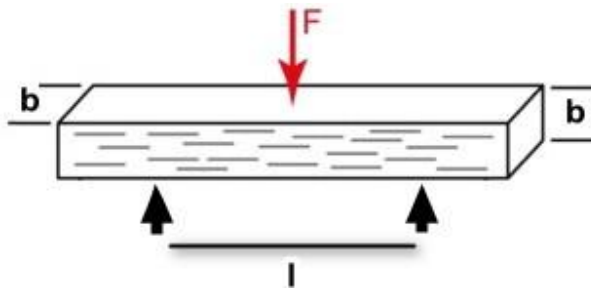


Figure IV. 13 Third point flexural test

Compressive test is carried out on the half-prisms (Figure IV. 14) resulting from the flexural test with a charging speed of 240 kN/s. Compressive strength σ_c is calculated as follows:

$$\sigma_c = \frac{F_c}{S} \quad (\text{Equation IV. 6})$$

With

- σ_c is the compressive strength (N/mm²),
- F_c is the maximum compressive load (N),
- S is the cross section of the beam (S = b × b) (mm²).

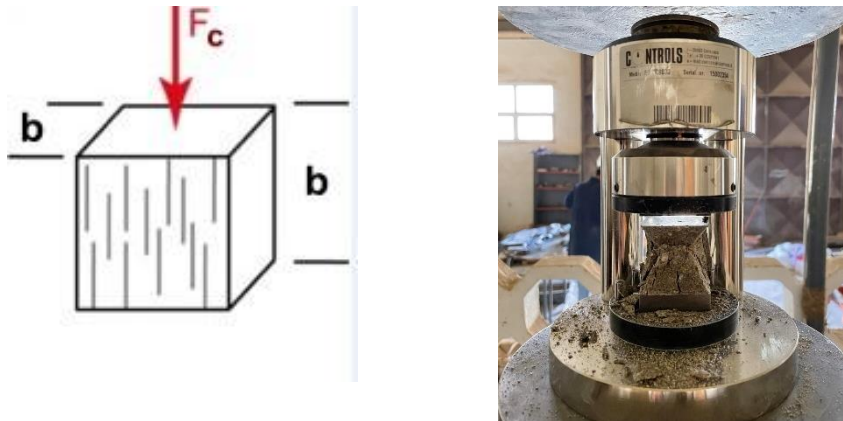


Figure IV. 14 Compressive test

IV.4.1.3 Modulus of elasticity

Modulus of elasticity (E_D) was carried out on (60×90) mm³ cylindrical repair mortar specimens using the ultrasonic pulse velocity test (UPVT) (Figure IV. 15) after 3, 7, 28 and 90 days of air curing in the laboratory ($T = 20 \pm 5^\circ\text{C}$, $\text{RH} = 30 \pm 5\%$), according to EN 12504-4 [224]. It consists on measuring the ultrasonic velocity of the pulses of longitudinal waves passing through concrete in the purpose of estimating the homogeneity and quality of the tested specimen [225]. The E_D is calculated with the equation below:

$$E_D = \rho v^2 \quad (\text{Equation IV. 7})$$

With

- E_D is the dynamic modulus of elasticity (MPa),
- ρ is the density of dry specimen (kg/m³),
- v is the ultrasonic velocity (km/s).



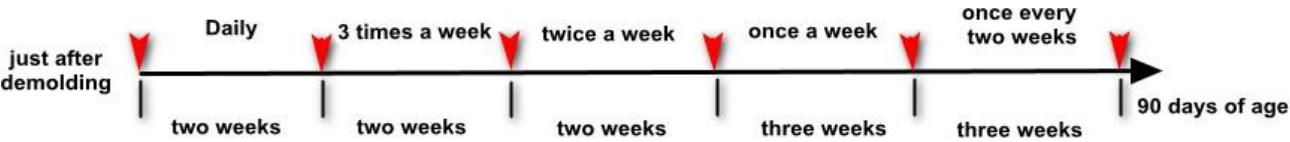
Figure IV. 15 Ultrasonic pulse velocity test

IV.4.1.4 Shrinkage

In this study, total shrinkage is measured on prismatic specimens $(40 \times 40 \times 160)$ mm³ with studs at the ends (Figure IV. 16) according to the standard EN 12617-4 [226]. Measurements were

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taken from the first day, just after demoulding, until 90 days of age. The variation of temperature and moisture during measurements were also recorded and presented in Table IV. 12. Shrinkage measures are taken as following:



Shrinkage is calculated according to the equation:

$$\Delta s = \frac{\Delta l}{l} \tag{Equation IV. 8}$$

With

- Δs is the shrinkage value,
- Δl is the length variation of the specimen between the measurement just after demoulding and the daily measurement (mm),
- l is the original length of the specimen (160 mm).

Table IV. 12 Variation of temperature and moisture during measurements.

Age (days)	1-3	7-11	16-18	21-23	25-27	30-34	36-39	42-56	70-90	120-258
T (°C)	22-24	22-24	14-18	16-18	16-17	17-18	15-18	11-13	11-15	11-15
RH (%)	20	20	20	20	25	27	25	28	26	27



Figure IV. 16 Moulds and shrinkage measurement

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IV.4.1.5 Thermal conductivity

Thermal conductivity (λ) test was carried out on $(40 \times 40 \times 160)$ mm³ after 28 days of curing in saturated-lime water ($T = 20 \pm 2^\circ\text{C}$, $\text{RH} = 100\%$) in accordance with the N-EN 993-15 standard [227]. The experimental protocol involves pre-drying the samples at a temperature of $65 \pm 5^\circ\text{C}$ until the stabilisation of their mass. Figure IV. 17 presents the measuring instrument.



Figure IV. 17 Thermal conductivity instrument

IV.4.1.6 Capillary absorption

Water absorption by capillarity test characterizes the capacity of a mortar to absorb and transmit water through capillarity. In this study, test is conducted at 28 and 90 days on prismatic samples of $(40 \times 40 \times 160)$ mm³ conserved in saturated-lime water ($T = 20 \pm 2^\circ\text{C}$, $\text{RH} = 100\%$) according to the European standard EN 1015-18 [228]. The tested specimens were dried in oven at a temperature of $65 \pm 5^\circ\text{C}$ for at least 48 h until mass stabilization. The lateral sides of the prisms were covered using an adhesive tape. Then they were placed vertically over a grid in water with 5 mm of depth (Figure IV. 18). The weight of the samples is recorded at different times: 4, 9, 16, 25, 49, 64, 120 and 1440 minute at an ambient temperature ($T = 20 \pm 2^\circ\text{C}$, $\text{RH} = 25\%$). The first two hours of water absorption were recorded to determine the initial absorption, known as the 'sorptivity'. Sorptivity coefficient (S) is the slope of the function of cumulative mass of water absorbed per unit area of the cross-section versus the square root of time using the following equation:

$$\frac{Q}{A} = S \cdot \sqrt{t} \quad (\text{Equation IV. 9})$$

With

- S is sorptivity coefficient ($\text{kg}/\text{m}^2 \cdot \text{h}^{1/2}$)
- Q is the amount of water absorbed (kg)

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- A is the area of the cross-section in contact of water (m^2)
- t is the time (h)

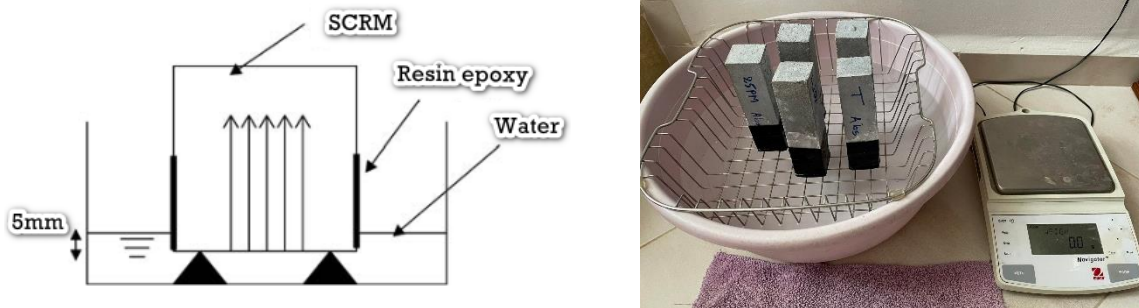


Figure IV. 18 Capillary absorption test

IV.4.1.7 Mercury intrusion porosity (MIP)

The porous structure of concrete is the responsible for moisture exchanges with the external environment. Studying concrete porosity can thus be useful for evaluating its microstructure, which may explain the results obtained for the shrinkage depending on its composition [69], thermal conductivity and ultrasonic velocity. In this context, Mercury intrusion porosity (MIP) was conducted on repair mortar specimens after 90 days of curing in saturated lime-water ($T = 20 \pm 2^\circ C$, $RH = 100\%$). MIP is applied to analyse the microstructure and pore structure of repair mortars containing different dosages of polypropylene fibres, marble powder and nano-silica.

The MIP method is about measuring capillary pressure [229], based on Laplace's capillary pressure law and Young's equation. It consists on forcing mercury into a porous material by applying pressure. This method provides extensive information on the pore network and its architecture [230]. The first injection of mercury is followed by a desorption, after that a second injection allowing for the definition of total, free, and trapped porosity.

IV.4.1.8 Adhesion by flexural test

Adhesion test was evaluated using bonding tensile method (Figure IV. 19.(d)) on prismatic composite specimens ($40 \times 40 \times 160$) mm^3 (half repair mortar/ half substrate mortar). Substrate mortar specimens were prepared and cast in ($40 \times 40 \times 80$) mm^3 moulds as shown in Figure IV. 19.(a) then cured in humid chamber ($T = 20 \pm 5^\circ C$, $RH = 80 \pm 5\%$) for 28 days. For better adhesion, substrate mortar was scratched, cleaned and humidified before the application of the repair mortar. These composite specimens were tested after 7, 28 and 90 days of air curing in

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real hot climate ($T = 40 \pm 5 \text{ }^\circ\text{C}$, $\text{RH} = 10 \pm 5 \%$) (Figure IV. 19.(c)). The mechanical characteristics of substrate mortar used in this study are set out in *Table IV. 13*.

Table IV. 13 Flexural and compressive strength of SM (MPa).

Age	7 days	28 days
Flexural strength	6.5	7.1
Compressive strength	32	40

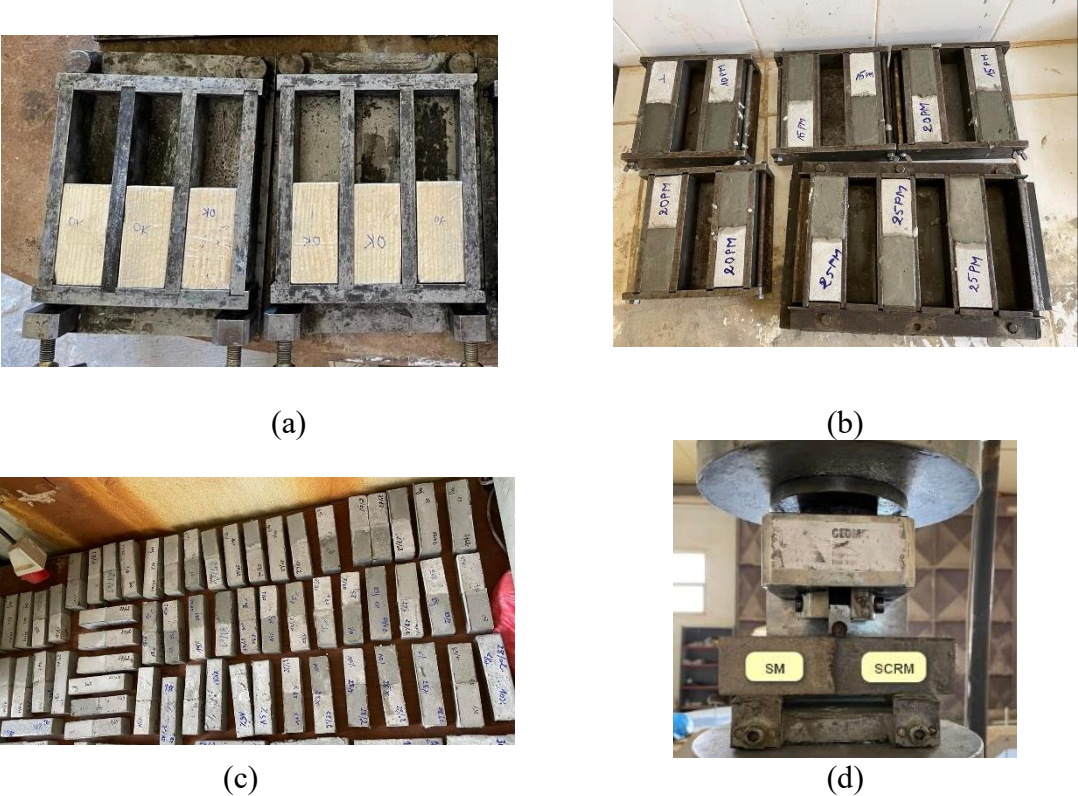


Figure IV. 19 (a) Empty moulds, (b) moulds filled with repair mortar, (c) curing specimens and (d) flexural test.

IV.4.1.9 Adhesion by slant shear test

To evaluate bond strength between repair mortars and substrate concrete, slant shear test was performed according to ASTM C882 (1999) [231]. Figure IV. 20 shows the bonding of two halves of a cylinder with slant elliptical plane inclined at 30° from vertical were bonded. The first half cylinder is the substrate concrete (SC) and the second is the repair material (RM).

Substrate concrete specimens were prepared and cast in plastic moulds containing wooden supports angled at 30° as shown in Figure IV. 20. After demoulding, specimens were conserved in humid chamber ($T= 20 \pm 5^\circ\text{C}$, $\text{RH}=80 \pm 5 \%$) for 28 days. The inclined surface of the substrate concrete is treated by sandblasting (under a pressure of 7 bars) Figure IV. 20, cleaned

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and humidified before pasting the repair material by reason of the fact that roughness of the substrate’s surface has a dominant effect on the bond strength [232].

The obtained composites (RM/ SC) are evaluated at 7, 28 and 90 days of air curing in real hot climate (T = 40 ± 5 °C, RH = 10 ± 5 %). An axial compression test was carried out according to ASTM C39 (2010) [233]. It is possible to obtain two types of failure modes, namely adhesive failure (at the interface) or cohesive failure (in repair, in concrete or in both of them). The bond strength using the slant shear test is calculated using the following equation:

$$\tau = \frac{4F (\sin 30)}{\pi D^2} \tag{Equation IV. 10}$$

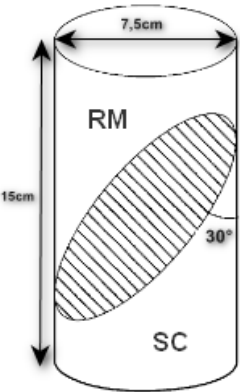
With

- τ is the slant shear strength of the composite samples (MPa),
- F is the global axial applied compressive force (N),
- D is the diameter of the cylinder (mm).

Mechanical characteristics of substrate concrete used in this study are set out in Table IV. 14.

Table IV. 14 Mechanical strength of substrate concrete (MPa).

Age	7 days	28 days
Flexural strength	5	6
Compressive strength	25	30



(a)



(b)



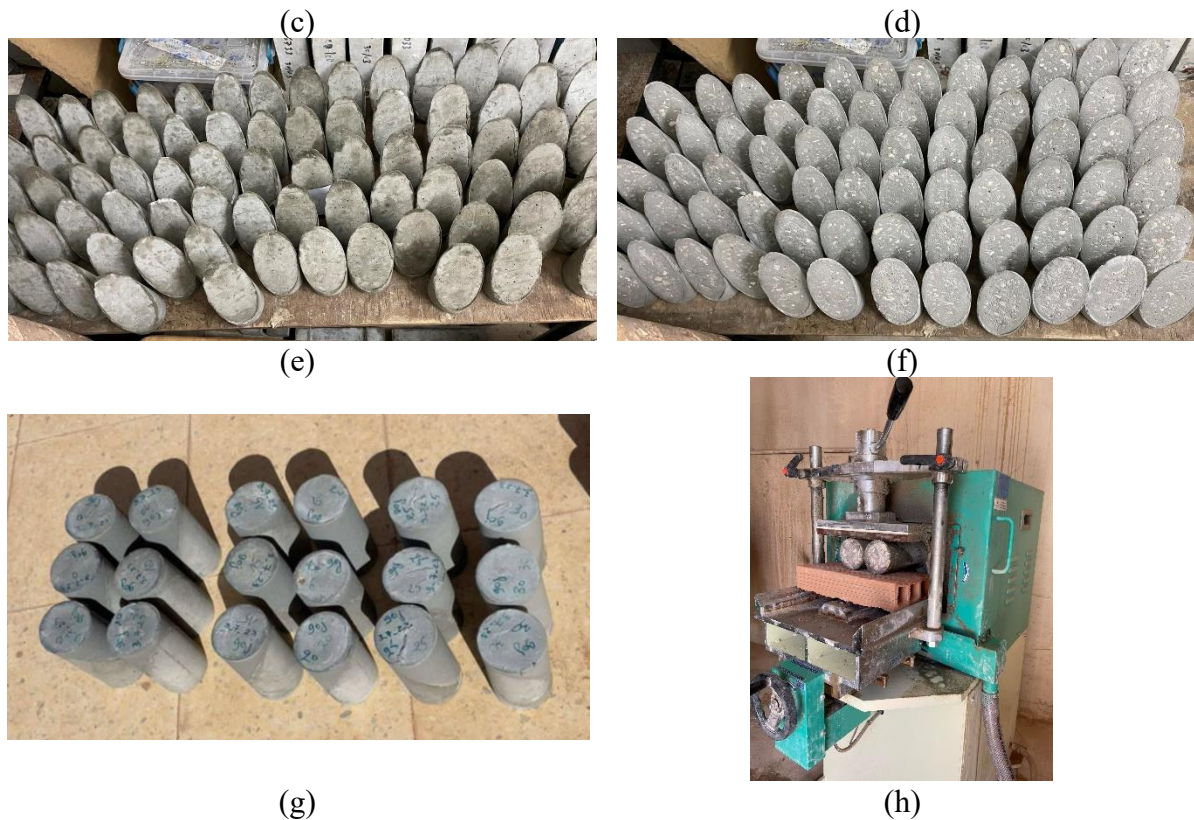


Figure IV. 20 Preparing concrete specimens for slant shear test.

IV.4.1.10 Compatibility by flexural test

To evaluate the compatibility between the RM and SC, flexural test was carried out using $(70 \times 70 \times 280)$ mm³ prismatic specimens. A recess of 1 cm of thick on the top of the substrate was filled with SCRM according to the standard ASTM C 78 (2009) as it is shown in Figure IV. 21. Substrate concrete was cured for 28 days in humid chamber ($T = 20 \pm 5^\circ\text{C}$, $\text{RH} = 80 \pm 5\%$), the surface of the recess of 1cm of thick was treated with sandblasting, cleaned and humidified before casting the RM. Flexural test was carried out after 7, 28 and 90 days of air curing in real hot climate ($T = 40 \pm 5^\circ\text{C}$, $\text{RH} = 10 \pm 5\%$). The faces filled with the repair mortars were placed in the stretched part as indicated (Figure IV. 21 (d)).

Substrate specimens for compatibility test were prepared and cast in $(70 \times 70 \times 280)$ mm³ prismatic molds. A recess of 1 cm of thick on the top of the substrate was filled with repair mortar according to the standard ASTM C 78 (2009) as it is shown in Figure IV. 21 (e). Substrate concrete was cured for 28 days in humid chamber ($T = 20 \pm 5^\circ\text{C}$, $\text{RH} = 80 \pm 5\%$), the surface of the recess of 1 cm of thick was treated with sandblasting, cleaned and humidified before casting the repair mortar.



Figure IV. 21 Preparing concrete specimens for compatibility by flexural test.

A flowchart of the experimental program is shown below
Figure IV. 22).

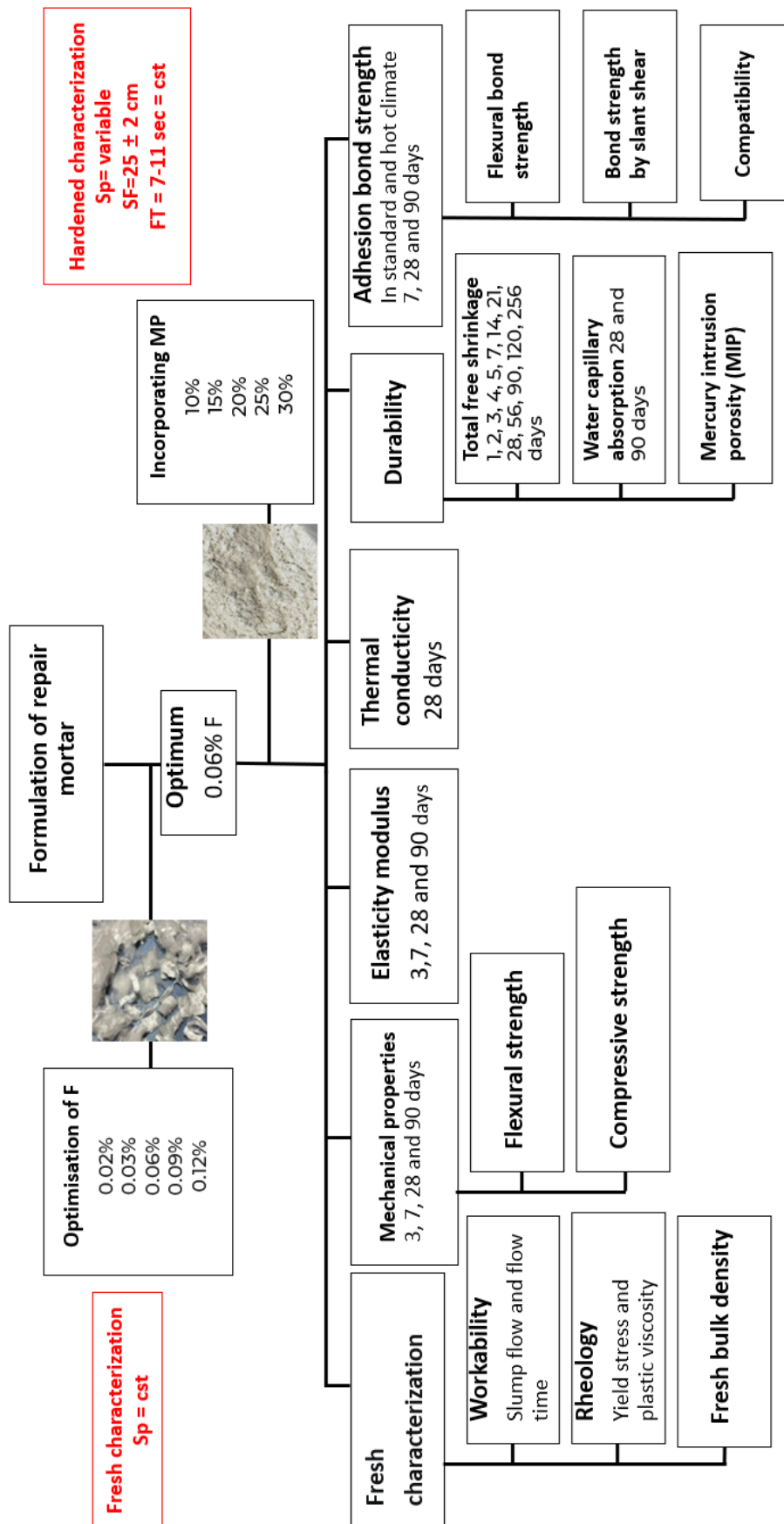


Figure IV. 22 Flowchart of the experimental program

IV.5 Conclusion

In this chapter, we presented the essential characterizations of the used materials, according to the requirements of the current standard, in order to produce fibre reinforced self-compacting repair mortars containing 10%, 15%, 20%, 25%, and 30% marble powder and polypropylene fibres. We also characterized these mortars according to the current standards using laboratory equipment. The fifth chapter is devoted to the presentation and discussion of the results of the mortars developed in this part.

Chapter V

Results and discussions

V.1 Introduction

The quality of a repair material depends on the quality of each component in the repair mix, on its workability, rheological properties, mechanical properties, dilatation, durability, adhesion and compatibility of the old concrete. However, these are not the only factors determining the final product. Indeed, the quality also heavily relies on the climatic conditions that the concrete is exposed to. To develop more environmentally friendly repair mortar, it is crucial to carefully select constituents and better understand the effects of temperature and hot climate on the durability of the reparation.

This chapter is dedicated to analysis and discussion of the obtained results from the various tests conducted on the developed self-compacting repair mortars (SCRMs) and substrate material, in both fresh and hardened states.

- Rheological properties of fresh mortar
- Mechanical properties
- Thermal properties
- Durability properties
- Adhesion and compatibility properties

V.2 Optimisation of fibre dosage

The main objective of this section is to determine the optimal dosage of polypropylene fibre from rheological and mechanical tests on fibre reinforced mortars. We note that in this section, S_p dosage was kept constant in all mixtures ($S_p = 0.6\%$) in order to determine the effect of PPF dosage on the fresh parameters.

V.2.1 Slump flow and flow time

The effect of polypropylene fibre dosage on slump flow and flow-time of self-compacting mortars is plotted in Figure V. 1. The results showed that adding 0.02% and 0.03% of fibres increases slump flow and decreases flow time compared to those of control mortar (CM0), while 0.06% of PPF gave to the same workability of that of CM0. Nevertheless, increasing gradually fibre percentage to 0.09% and 0.12% affects negatively slump flow and augmented flow time. These results are in line with those obtained by Bentegri [234], they introduced 0.12%, 0.24% and 0.36% of PPF and resulted in workability loss with the increment of fibre dosage. Other researcher concluded that the incorporating of fibres reduces the workability [110].

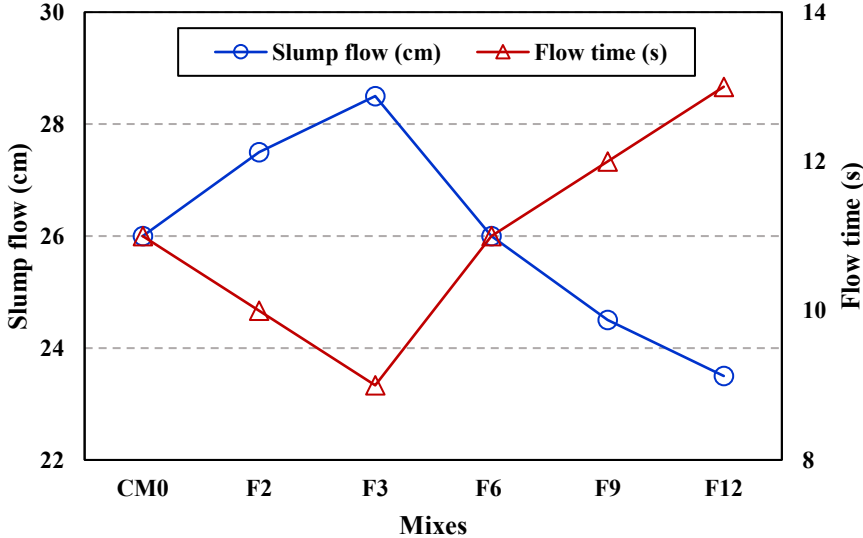


Figure V. 1 Effect of fibre dosage on workability properties

At small dosages 0.02% and 0.03% of PPF, workability was enhanced thanks to smooth surface, small cross section and flexible behaviour of PPF that allows fibres to move within the paste. However, high fibre dosage causes additional friction between the particles leads to loss in the flowability and workability in mixes F9 and F12.

V.2.2 Plastic viscosity and yield stress

Yield stress and plastic viscosity in function of fibre dosage are presented in Figure V. 2. The same trend of flow time is observed in yield stress and plastic viscosity. At small dosages of PPF (0.02% and 0.03%) a decline in both rheological parameters is obtained. Beyond 0.03% PPF, an augmentation was recorded. This increase is due to the modification of granular structure and the decrease in maximum compaction in addition to its high specific surface area [234]. Furthermore, the presence of fibres blocks the movement of aggregates during the rheological test (shearing movement), leading to an increase in rheological parameters. Except for 0.12% PPF a drop occurs due to segregation; it is attributed to an excessive accumulation of fibres adhering to the sand particles in the vane. It can be noticed that mortar with 0.06% of PPF has the same slump flow and flow time as that of control mortar (CM0) without fibres however, they have different rheological parameters. There is a good correlation between slump flow and flow time and rheological parameters in all mixtures, except in mortar F12 that showed fibre agglomeration.

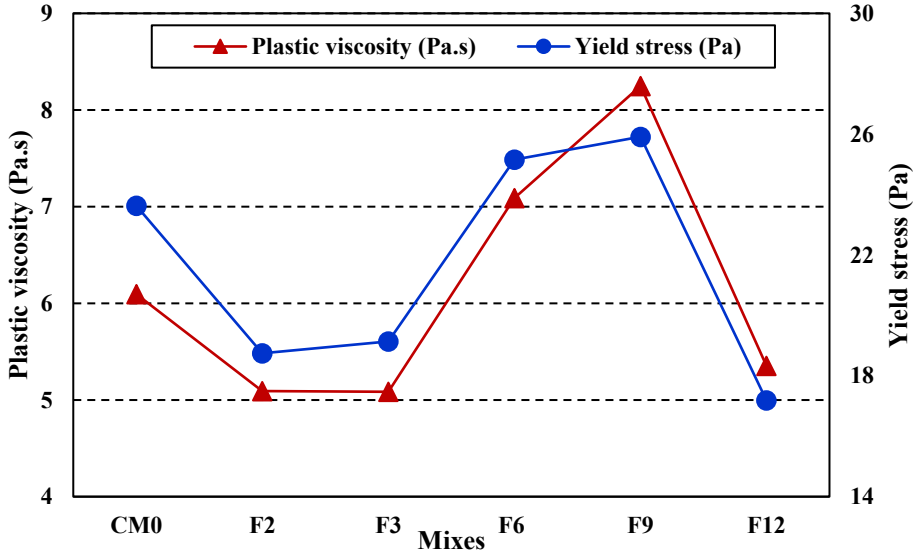


Figure V. 2 Rheological properties variation in function of fibre dosage

V.2.3 Fresh bulk density

Figure V. 3 illustrates fresh bulk density of self-compacting mortar reinforced with PPF. From the results it is well observed that the addition of PPF has no impact on fresh bulk density due to the low density of PPF. Similar results were obtained by Hassanpour et al. [235] they studied the effect of polypropylene fibres and metallic fibres on fresh concrete performance. They concluded that the addition PPF has no significant effect on concrete fresh density contrary to metallic fibres that have high density.

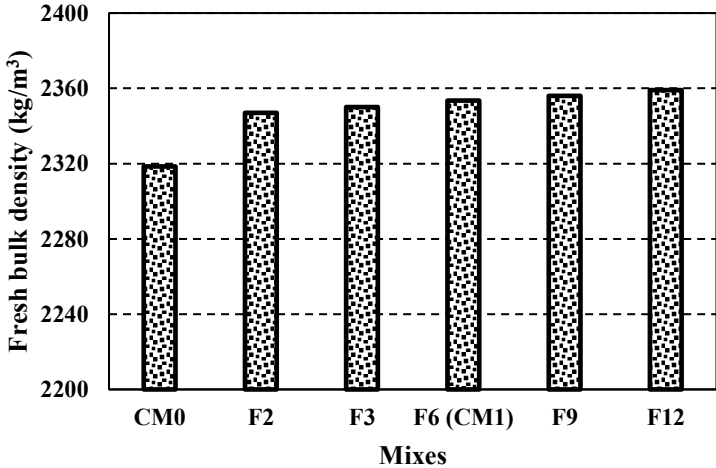


Figure V. 3 Fresh bulk density variation with fibre dosage

V.2.4 Compressive and flexural strength

The variation of compressive and flexural strengths of mortars reinforced with polypropylene fibres in function of fibre dosage at 28 days is given Figure V. 4. Adding PPF to the mix showed insignificant development in compressive strength compared to control mix without fibres CM0 except for mortar F6(CM1) that showed a slight enhancement. It could be related to the

achievement of the maximum compactness of the mixture granular, which improves the fibre's distribution and orientation in the mixture [234]. Consistent results are achieved by Das et al. [236], they concluded that using 0.5% of PPF has no impact on compressive strength. On the other hand, other study resulted that increasing PPF dosage to 0.24% and 0.36% led to significantly decline compressive strength of concrete [234].

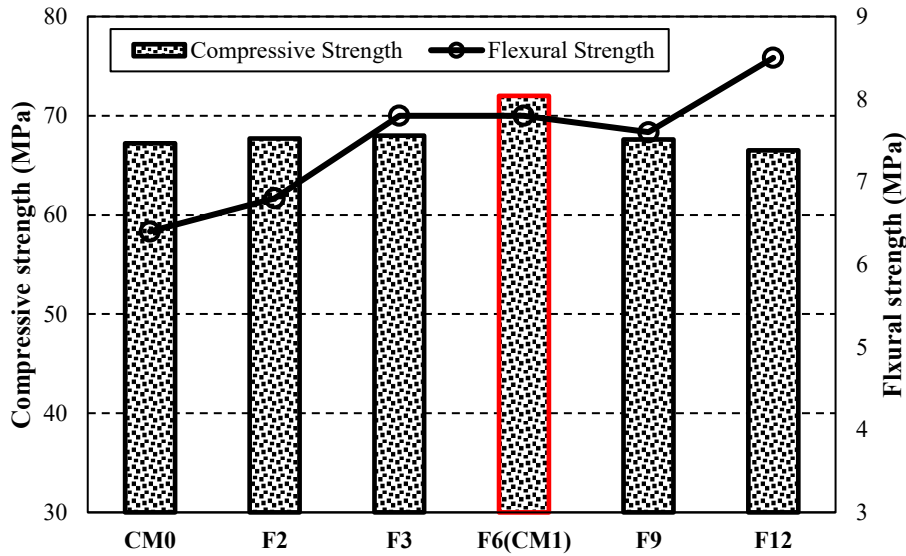


Figure V. 4 Mechanical properties development at 28 days in function of fibre dosage

Flexural strength is directly affected by fibre incorporation; a significant gain is obtained. The highest strength revealed to mortar with 0.12% of PPF. Increasing fibre content increases gradually flexural strength and ductility, thanks to the bridging effect that transfers charges from the matrix to the fibres. These results are supported by the findings of previous studies. They reported that the inclusion of PPF is responsible for strength increment where PPF inhibited the formation and propagation of the early cracks [237]. From the obtained results, 0.06% of PPF is the optimal mix, for that reason it was chosen as a second control mortar (CM1).

V.3 Effect of marble powder

The main purpose of this section is to determine the effect of the substitution of cement by MP on the properties of mortars reinforced with 0.06% of PPF. We note that Sp dosage was kept constant in all mixtures ($S_p = 0.6\%$) in order to determine the effect of MP only on the fresh parameters (see Table IV. 11). In regards of hardened state, Sp dosage was adjusted to obtain the slump flow required by EFNARC 2005 [61]. Where slump flow diameters of all mixtures are in the target of 25 ± 2 cm, and the flow time varies between 7-11 sec (see Table IV. 10).

V.3.1 Rheological properties

V.3.1.1 Slump flow and flow time

The effect of incorporating MP into mix with 0.06% PPF on slump flow and flow-time is presented in Figure V. 5. Increasing marble powder amount in cement substitute binder enhances the slump flow and declines flow time. That could be attributed to the filling and dilution effect of MP which increases the mobility of the cement particles [238]. Moreover, at an early phase of hydration, the inert nature of MP, releases a part of the mixing water which causes lubrication of the grains, and improves the mixture's workability [238].

These findings are in line with those found by Belaidi [239]. He observed that increasing marble powder from 5% to 30% as ordinary cement replacement shows its beneficial effect on the workability gain. Similar observations were noted by Boukhelkhal et al. [240], where the substitute of cement by PM was found to be very favourable in terms of improving workability and rheological parameters. Moreover, Adjoudj [241] concluded that the addition of limestone fillers in mortar has a remarkable fluidifying and a filler effect that contributes in improving the workability without the use of superplasticizer. Other researchers recorded that limestone fillers fill the inter-particle voids of the mortar and increase the compactness Φ^* paste of the mixture which leads to release the water trapped in the voids and improving the workability [242]. Also, Alyousef et al. [156] observed that the flow of self-compacting concrete was enhanced when the amount of marble powder increases, this is related to the decrease in viscosity of SCC when the paste volume increases.

V.3.1.2 Plastic viscosity and yield stress

The variation of rheological properties of mortars with PPF in function of MP dosage is given in Figure V. 6. By adding MP as cement substitution, both plastic viscosity and yield stress showed a decline compared to control mortar (CM1), as a consequence of the improvement of slump flow diameter. This decline is more pronounced beyond 15% of MP. That could be caused by the augmentation in the paste volume due to the low bulk density of MP compared to that of cement which helps to separate the sand particles one another. Consequently, the friction between the particles is reduced, leading to the improvement of the fluidity [238].

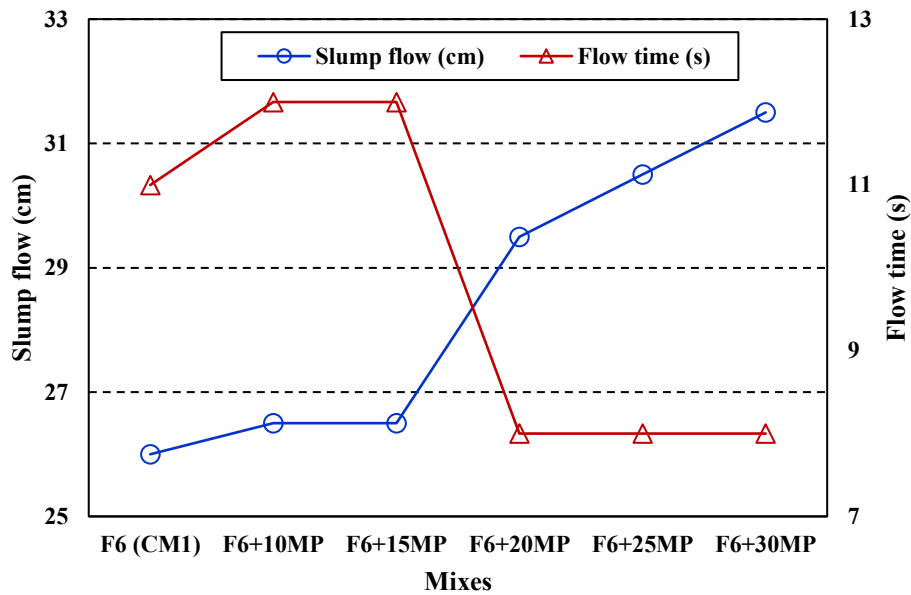


Figure V. 5 Effect of marble powder on workability properties

However, the impact of increasing the amount of PM is more notable at 25% PM, showing a reduction of 27% and 40% in both plastic viscosity and yield stress, respectively, compared to the control mortar. In contrast, at 30% substitution rate, the effect of PM on the rheological parameters of SCRM becomes less pronounced, with only an 18% of reduction in plastic viscosity compared to control mortar. These findings are similar to the conclusion of Dada [238], it's recorded that at a substitution of 40% of MP, the mortar becomes more viscous due to the increase in paste compactness (Φ^*) and the relative solid concentration (Φ/Φ^*) in the paste. It can be concluded that the addition of different amounts of MP to the cement matrix of mortars improves the rheological parameters, slump and flow time.

Nevertheless, at a given concentration above the critical dosage, where maximum compaction is achieved, a considerable increase in viscosity is expected [242]. The viscosity rise beyond this dosage can be explained by the enhancement in interparticle friction caused by the increase in solid-solid contact.

These results are in consistent with previous findings conducted by Topçu et al. [243], Corinaldesi [244] and Alyamaç and Ince [245], which revealed that marble powder with its limestone origin can be successfully and economically used as a filler in mortars and concrete. In the presence of a superplasticizer, the introduction of marble powder gives concrete mixtures excellent rheological behaviour and improves its resistance to segregation with Water/Cement ratio below 0.5.

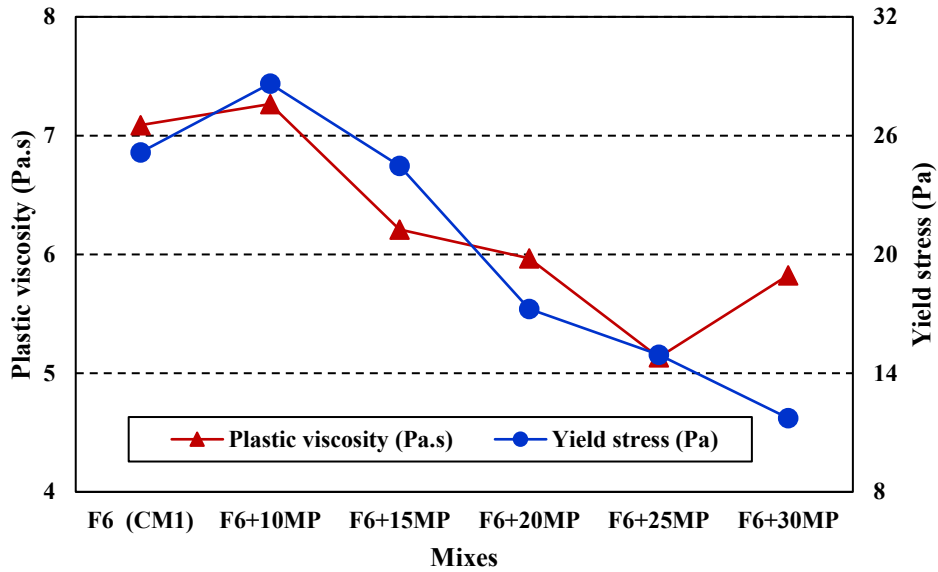


Figure V. 6 Effect of marble powder on rheological properties

Correlations between workability and rheological properties based on linear relationships are illustrated in Figure V. 7 and Table V. 1. Good relation is obtained between flow time and slump flow as well as slump flow and yield stress. There is a moderate correlation between yield stress and plastic viscosity. However, a low relation exists between flow time and plastic viscosity. Some authors incorporated MP (at 0%, 5%, 10%, 15%, and 20%) in self-compacting concrete. They estimated correlations using empirical equations and reported that there is an excellent relationship between yield stress and slump flow besides of a relationship between flow time and plastic viscosity with correlation coefficient of ($R^2 = 0.90$ and $R^2 = 0.93$), respectively [137]. This difference in correlation coefficient (R^2) is probably due to the difference in the studied granular scale (self-compacting mortar/ self-compacting concrete), number of points and number of variables (PPF and PPF+MP).

V.3.1.3 Fresh bulk density

The impact of adding marble powder on fresh bulk density of repair mortars is illustrated in Figure V. 8. Incorporating marble powder up to 15% MP caused a drop in density about 4% then a rise is observed up to 30% MP. It can be noted that adding 10% and 30% MP showed a comparable density. Comparing to control mortar F6(CM1), all mixtures have lower density. This could be due to the lower specific density of MP (2.62 g/cm^3) relative to the cement (3.03 g/cm^3). Similar results was recorded by [160], that the use of up to 20% MP led to decrease the density of fresh concrete.

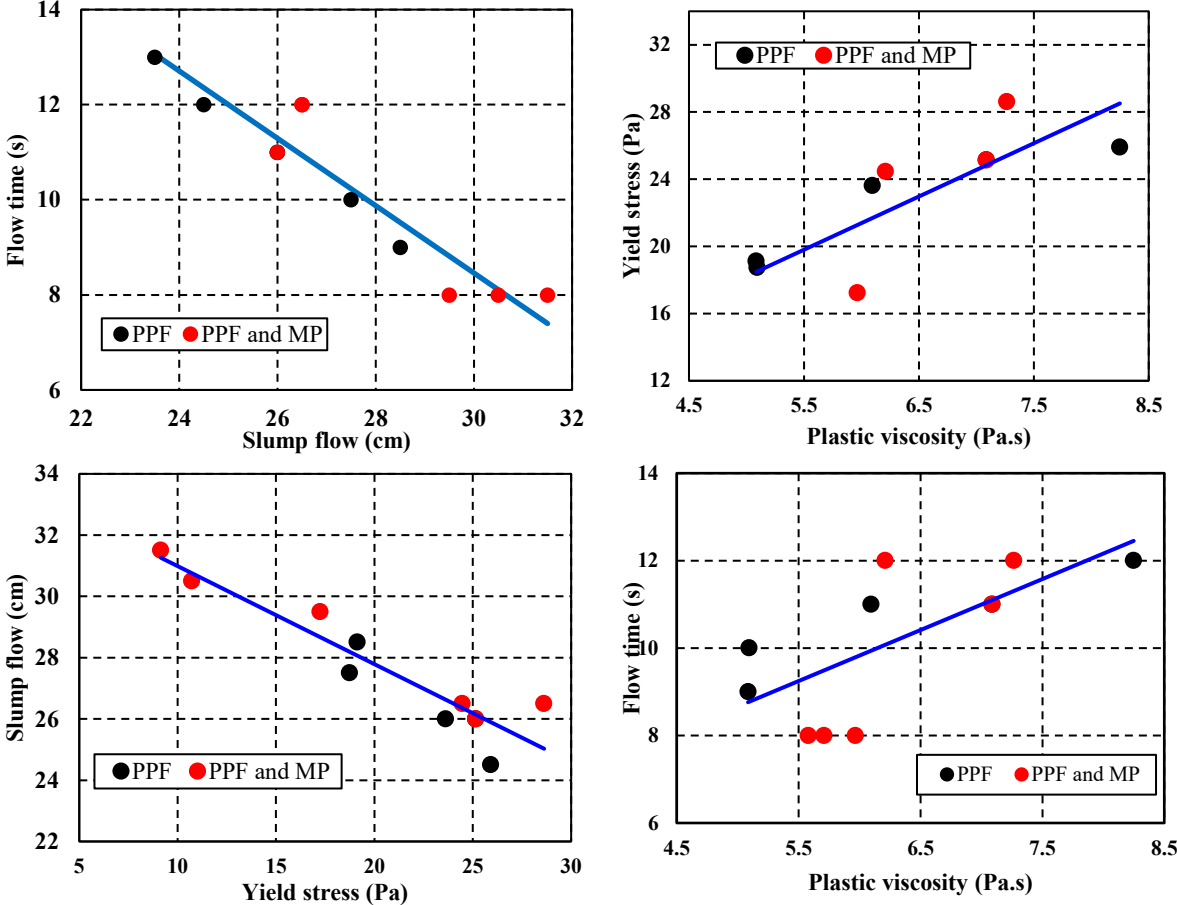


Figure V. 7 Correlation between workability and rheological parameters of all series

Table V. 1 Equations and correlation coefficients between workability and rheological properties.

Correlation between	Equation	Coefficient of determination R²
Flow time (FT) and Slump flow (SF)	FT = -0.708 SF + 29.700	0.887
Yield stress (YS) and Plastic viscosity (PV)	YS = 3.169PV + 2.372	0.660
Flow time (FT) and Plastic viscosity (PV)	FT = 1.166PV + 2.834	0.468
Slump flow (SF) and Yield stress (YS)	SF = -0.320YS + 34.188	0.866

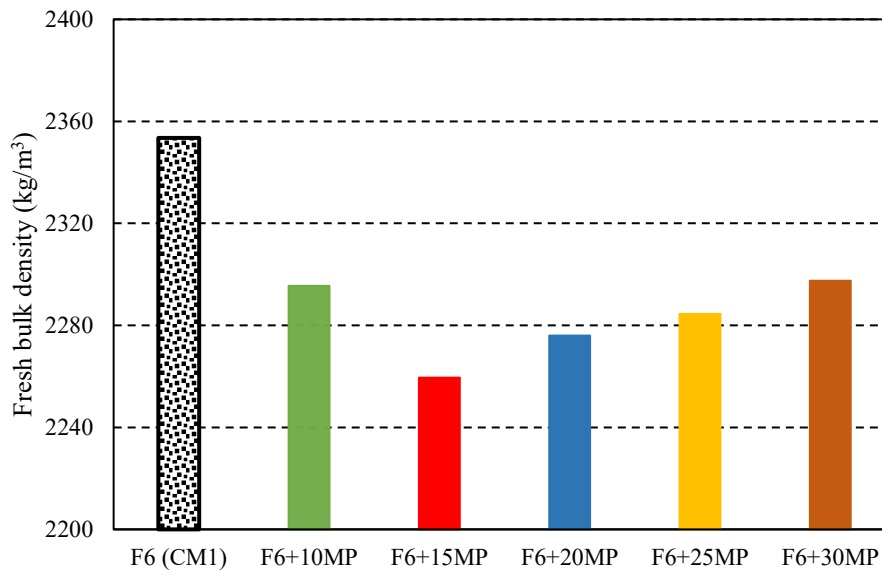


Figure V. 8 Fresh bulk density variation in the presence of MP

V.3.2 Mechanical properties

V.3.2.1 Compressive strength

The evolution of compressive strength of self-compacting repair mortars reinforced with 0.06% of polypropylene fibre in function of marble powder dosage at 3, 7, 28 and 90 days is illustrated in Figure V. 9. We note that all repair mortars exhibited compressive strength higher than 45 MPa at all ages, fulfilling the requirements of class R4 materials according to the [246] Standards.

It is observed that the compressive strength increases with the proceeding in curing times from 3 to 90 days, while, it decreases with increasing the substitution levels of marble powder. The gain rate in compressive strength from 3 days to 7, 28 and 90 days of conventional mortar is higher than that of mortars with MP.

At an early age (3 days), a comparative value of compressive strength is generated in all mortars compared to control mortar. That could be attributed to micro filler effect of MP which fill the voids and lead to denser paste [247]. In addition to its contribution in improving the transition zone and cement paste [248]. At 7 days, 10% of MP content gives an augmentation in compressive strength about 8% compared to control mortar, while a reduction was observed with the increase of MP. A slight and insignificant diminution was generated in all self-compacting repair mortars at 28 days compared to control mortar. At later age (90 days), the strength started to decrease at higher level from 20% of replacement. This diminution in the strength gain is possibly due to the reduction in hydration products C_3S and C_2S , as it was recorded in previous studies [249–252].

Singh et al. and Kore et al. [248,253] observed that for 10% and 15% replacement level, the compressive strength increases then starts decreasing for 20% and 25% of replacement at 28 days of curing. Aliabdo et al. [254] noted that compressive strength enhanced with 10% replacement level of cement by MP. Since that lime-stone fine has similar mineralogical composition to marble powder, Voglis et al. and Guemmadi et al. [255,256] indicated that lime-stone fine reacts with the alumina pastes of cement to form a calcium non-carbo aluminate hydrate phase which result in significant enhancement in strength, despite that lime-stone fine does not have a pozzolanic reaction. Singh et al. [248] recorded that many factors can influence the reactivity of the marble powder such as its fineness. In order to obtain a compressive strength close to that of control concrete, using the entire sample passing through 300 μm sieve could be beneficial.

According to the results, the replacement of cement by MP up to 20% showed insignificant change in compressive strength, that could be due to the high fineness of MP. However, at higher replacement a decline by about 12% is observed compared to control mix F6(CM1) which contains fibres only. Diminishing cement binder cause a dilution of the cementing phases (C_2S and C_3S) responsible for increasing the strength of cement-based materials, ultimately producing a less dense concrete with high porosity [257,258].

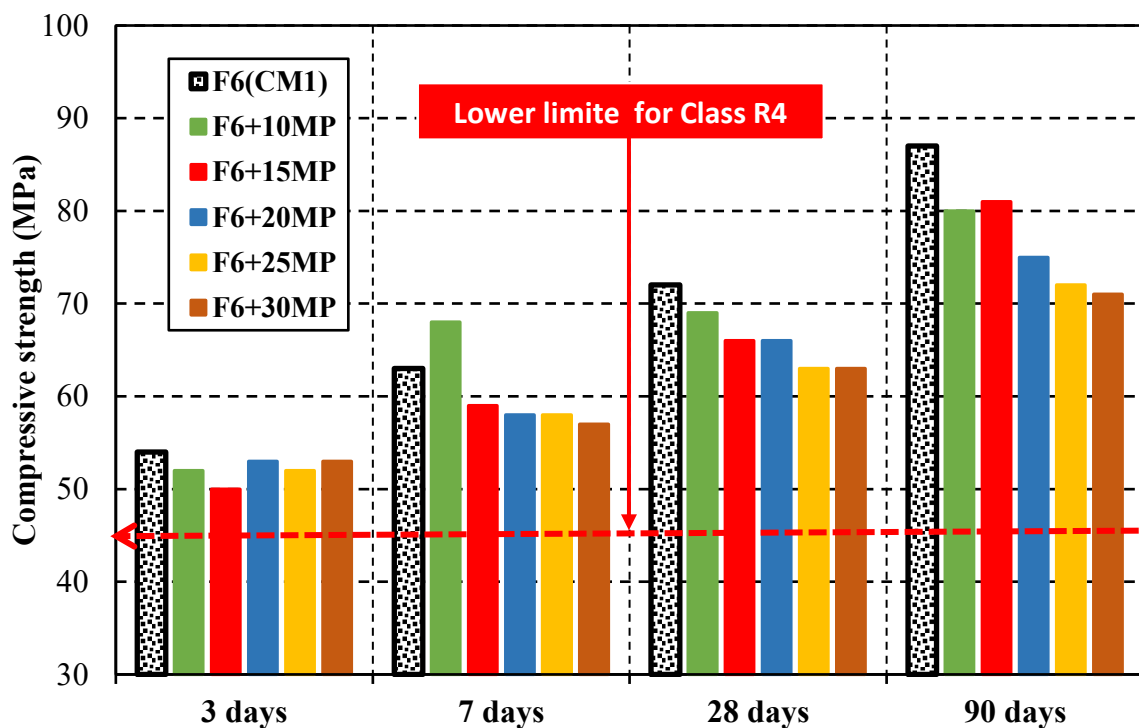


Figure V. 9 The influence of marble powder on compressive strength at 3, 7, 28 and 90 days

V.3.2.2 Flexural strength

Concerning the results of flexural strength, its trend was similar to that of compressive strength as shown in Figure V. 10. An increase is observed in function of age, and a diminution in strength after adding MP. At 3 days, F6+10MP showed an enhancement about 16.3% compared to control mortar, while F6+15MP, F6+20MP and F6+25MP gave a comparable value. A decline about 12.2% was generated in F6+30MP. At 7 days, F6+10MP gave the same strength as that of F6(CM1), while a reduction was observed in the other mixtures. A decrease in strength is observed at 28 days, except for F6+15MP exhibited the same strength value with F6(CM1). At longer age (90 days), the use of MP leads to a diminution in flexural strength, it is well observed from 15% of MP. This decrease is a consequence to the reduction in C₃S and C₂S required for hydration process and responsible for strength development [259,250,251,260]. Agarwal and Gulati [261] reported that 10% and 20% of substitutions by MP resulted in disadvantages in performance of 12% and 25%, respectively, after 180 days of curing.

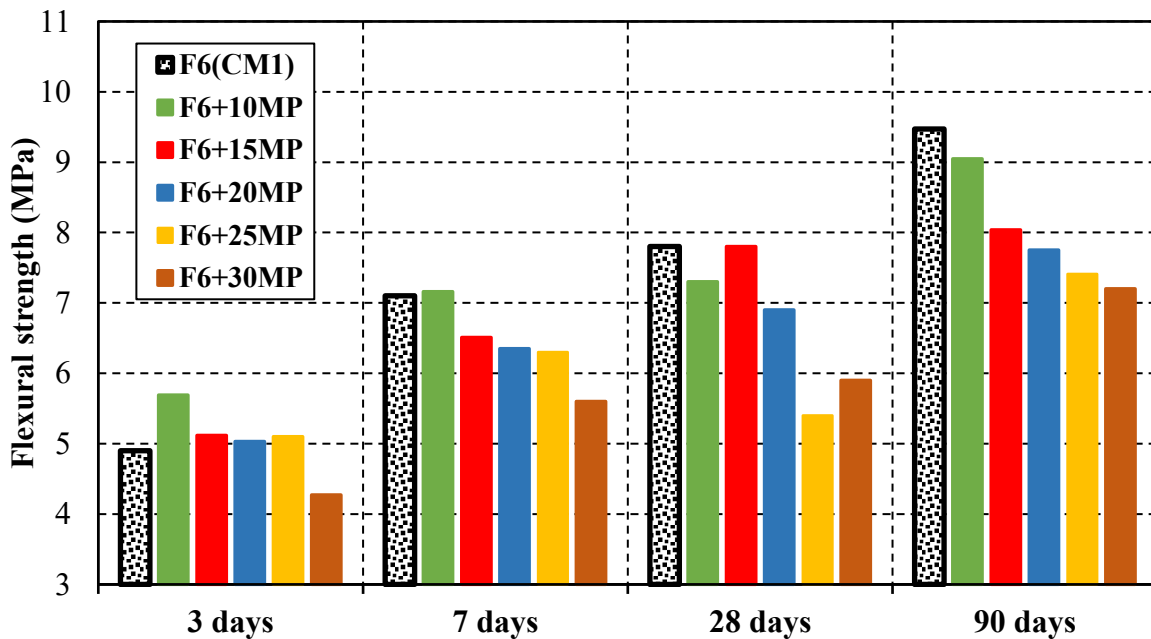


Figure V. 10 The influence of marble powder on flexural strength at 3, 7, 28 and 90 days

Correlation between compressive and flexural strengths as outlined by various researchers can be summarized in a different way:

$$f_r = k f_c^\alpha \quad (\text{Equation V. 1})$$

Where f_c represents compressive strength in MPa and f_r is flexural strength in MPa. Correlation between compressive and flexural strength findings proposed in this investigation,

is represented the equation below. It was used to model the correlation among compressive and flexural strength for SCRM mixtures. Coefficients k and α were obtained through nonlinear regression analysis using the test results, which were considered as the main variables are 0.048 and 1.2, respectively. The corresponding a strong correlation coefficient $R^2= 0.83$ can be expressed as follows:

$$f_r = 0.048 \cdot f_c^{1.2} \tag{Equation V. 2}$$

This expression can be effectively utilized to estimate and predict compressive strength using the findings obtained from the flexural strength test, as illustrated in Figure V. 11.

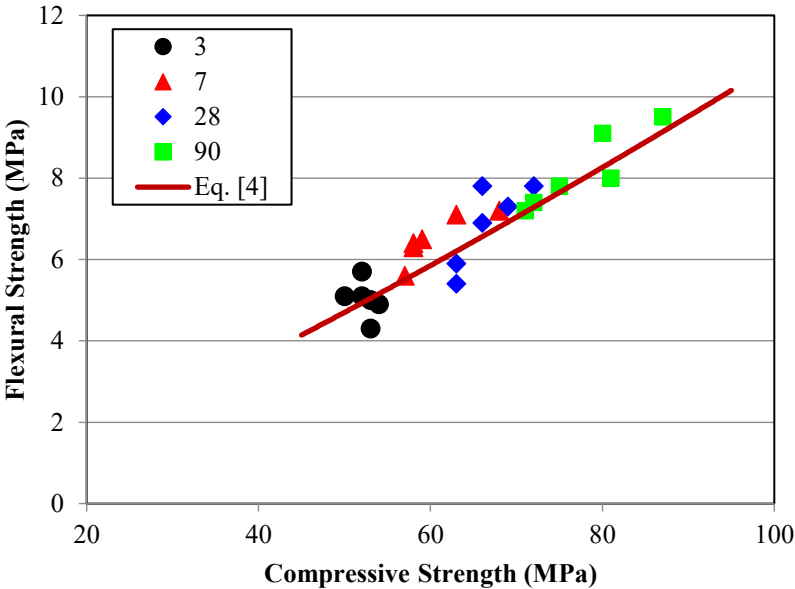


Figure V. 11 Correlation between flexural and compressive strengths of SCRM at all ages

V.3.3 Elasticity modulus

Elasticity modulus (E_D) was carried out at 3,7, 28 and 90 days and plotted in Figure V. 12. From the graph, it’s observed that modulus of elasticity showed a development with time in all mixtures. It’s also noted that that modulus of elasticity follows the same trend of the compressive strength, where the increment in marble powder replacement led to diminish E_D value. The highest modulus values are recorded to CM1 at all ages thanks to the high content of cement. The decrease in E_D could be due to the diminution in the volume of hydration

products compared to control mortar and to the evaporation of water necessary for the hydration in case of air-cured conditions.

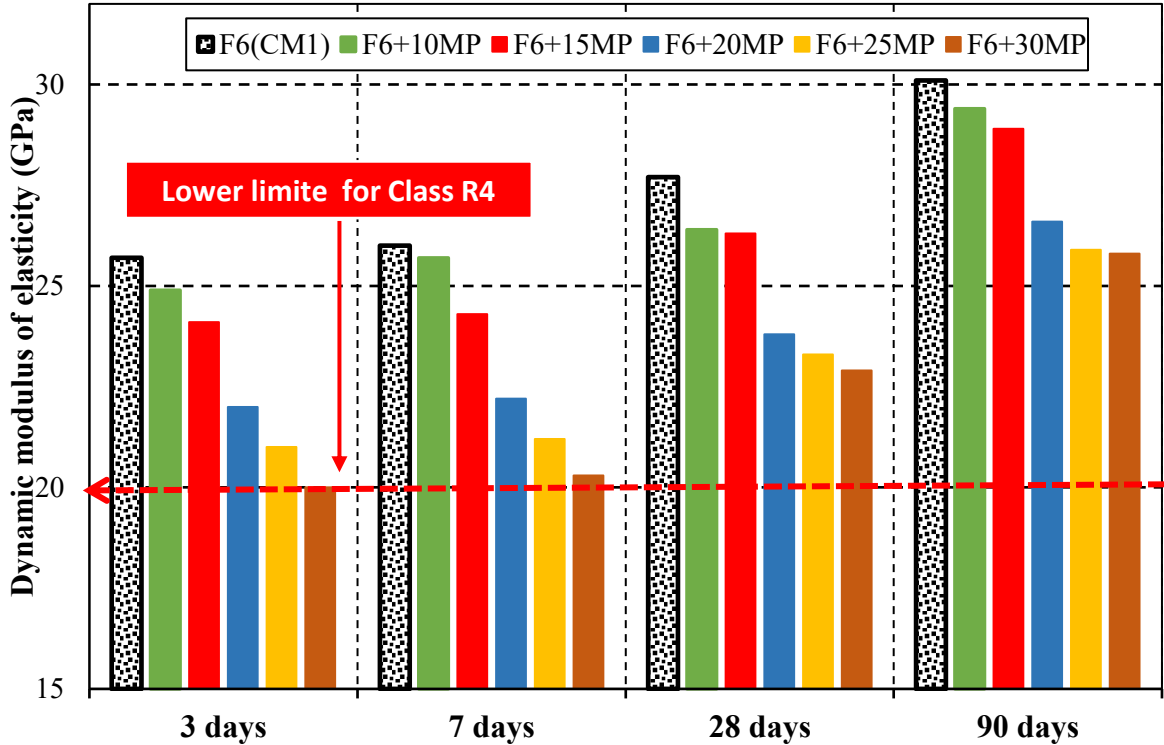


Figure V. 12 Elasticity modulus at 3, 7, 28 and 90 days of SCRMs

All E_D values were higher than the lower limit (20 GPa) required by the EN 1504-3 Standards for Class R4 repair mortars. The high fineness of MP led to fill the voids and enhance the compactness of the specimen. Several researchers reported that composite materials are effective and good repair materials because of their high ductility [262–264]. Uysal and Yilmaz [265] indicated that E_D value declines with increasing the replacement rates of mineral admixtures. Other researchers found that using both PPF and recycled aggregates lead to a decline in E_D .

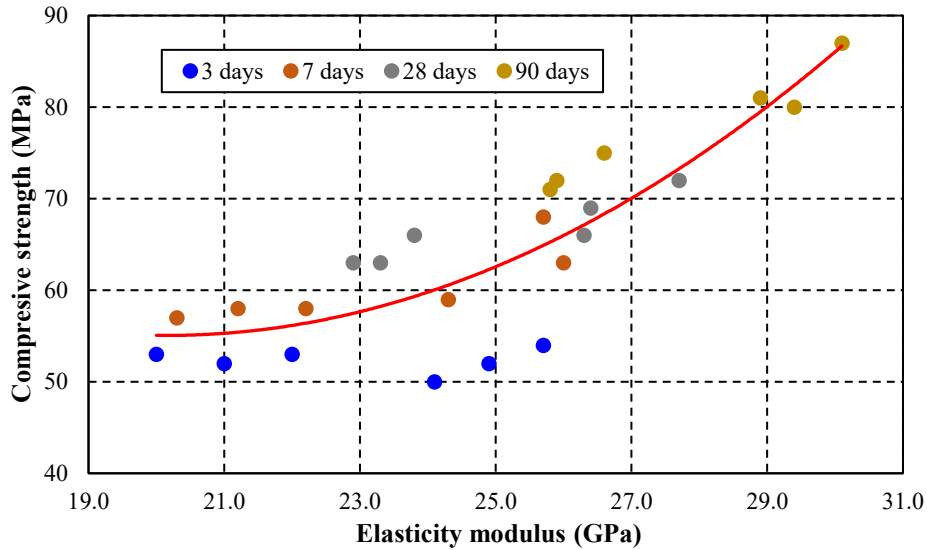


Figure V. 13 Correlation between compressive strength and elasticity modulus at all ages of SCRMs

A good correlation exists between compressive strength and elasticity modulus of self-compacting repair mortars at all ages as illustrated in Figure V. 13. the correlation is summarized in the following equation:

$$y = 0.3195x^2 - 12.878x + 184.83 \quad (\text{Equation V. 3})$$

Where coefficients x and y are modulus of elasticity in GPa and compressive strength in MPa, respectively. The corresponding a strong correlation coefficient $R^2 = 0.744$.

This expression can be effectively utilized to estimate and predict compressive strength using the findings obtained from the elasticity modulus test, all without causing any damage to the specimens.

V.3.4 Capillary absorption (sorptivity)

Sorptivity is defined as the diffusion and infiltration of water in cement matrix. It depends on the rate of water penetration and permeation through capillary pores and interfacial transition zone (ITZ) of the cement matrix [65]. The results of capillary absorption (S) at the age of 28 and 90 days is plotted in Figure V. 14. The coefficient S varies between 0.25 kg/m².h^{1/2} to 0.53 kg/m².h^{1/2} at 28 days, and between 0.08 kg/m².h^{1/2} to 0.25 kg/m².h^{1/2} at 90 days. Capillary absorption is often measured to predict the durability of the material [266].

It's well observed that the use of marble powder up to 20% increases significantly the coefficient of sorptivity at 28 days from 0.25 to 0.53 kg/m².h^{1/2}. Control mortar presented the lowest sorptivity compared to all repair mortars, while F6+20MP gives the highest coefficient. A comparable value was observed with 10%, 15%, 25% and 30% of MP. This could be

explained by the diminution in the volume of hydration products compared to control mortar due to the inert nature of marble powder. Boukhelkhal et al. [128] found that the increase in the amount of substituted MP leads to an increase in the water absorption of SCC at 28 days. Many researchers reported that sorptivity is directly related to formation of C-S-H gel, C-H crystalline and filling the pores [267,268]. Other investigation concluded that the use of marble waste particles finer than 150 microns to replace cement in ranges of 5%, 10%, 15% and 20% reduced water absorption by more than 40% [269].

Similar trend of 28 days is observed at longer age 90 days, an increase in sorptivity coefficient with the use of up to 20% MP then it starts in decreasing. A reduction of more than 50% is recorded in all mixtures from 28 to 90 days. This result could be related to the continuous cement hydration process with time. This is in line with the results of Choudhary et al. [270] they recorded that the incorporation of waste marble powder increases surface water absorption.

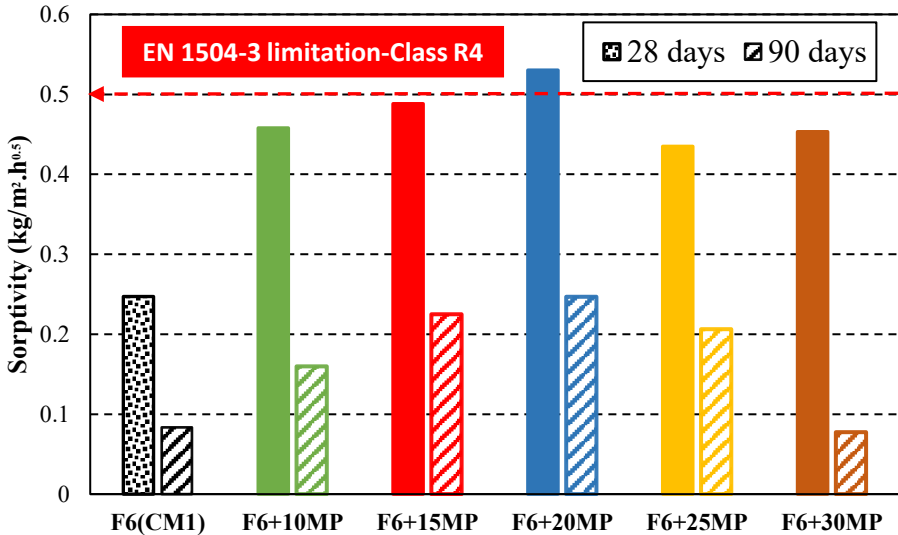


Figure V. 14 The impact of marble powder on sorptivity coefficient at 28 and 90 days

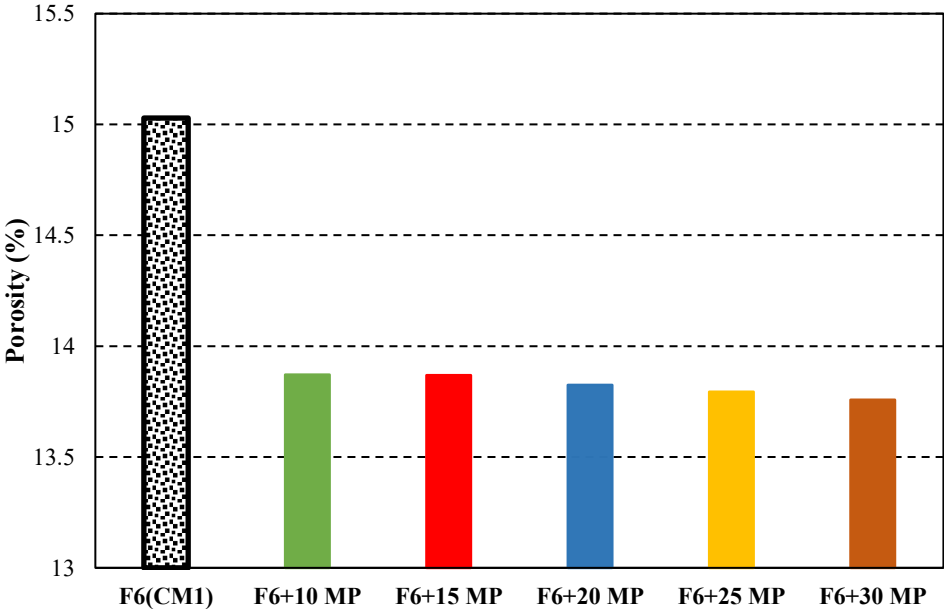
Other authors investigated the use of MP and found that water absorption decreases gradually when increasing MP up to 20% [250]. Benyahia et al. [70] indicated that the substitution of 10% of limestone dust gave a capillary absorption coefficient about 0.48 kg/m².h^{1/2}. Choucha et al. [271] used naturel pozzolana (NP) as a cement replacement with a fineness of 4100 cm²/g and reported that a high volume of (NP) increases significantly capillary absorption at 28 days. Abu sayed Mohamed Akid et al. [237] studied sorptivity of concrete containing 0%, 0.06%, 0.12% and 0.18% of polypropylene fibres and 15% of fly ash. They concluded that the samples with 0.06% PPF and 15% fly ash as well as 0.12% PPF and 15% fly ash exhibited the lowest

sorptivity coefficient compared to control concrete. Amin et al. [272] found that the use of up to 20% of glass powder reduces sorptivity coefficient about 39% compared to control concrete at 28 days.

As a conclusion, all the repair mortars meet the requirement for class R4 ($<0.5 \text{ kg/m}^2/\text{h}^{0.5}$) according to the EN 1504-3 except F6+20MP.

V.3.5 Mercury intrusion porosity (MIP)

Porosity is the ratio of total pore volume to sample volume. In MIP, the total pore volume corresponds to the cumulative mercury volume. Porosity and pore size distribution of a material provide important information about its durability. The pore size distribution and the existence of both large and small pores in mortars are critical factors for the material performance against environmental wear conditions [273].



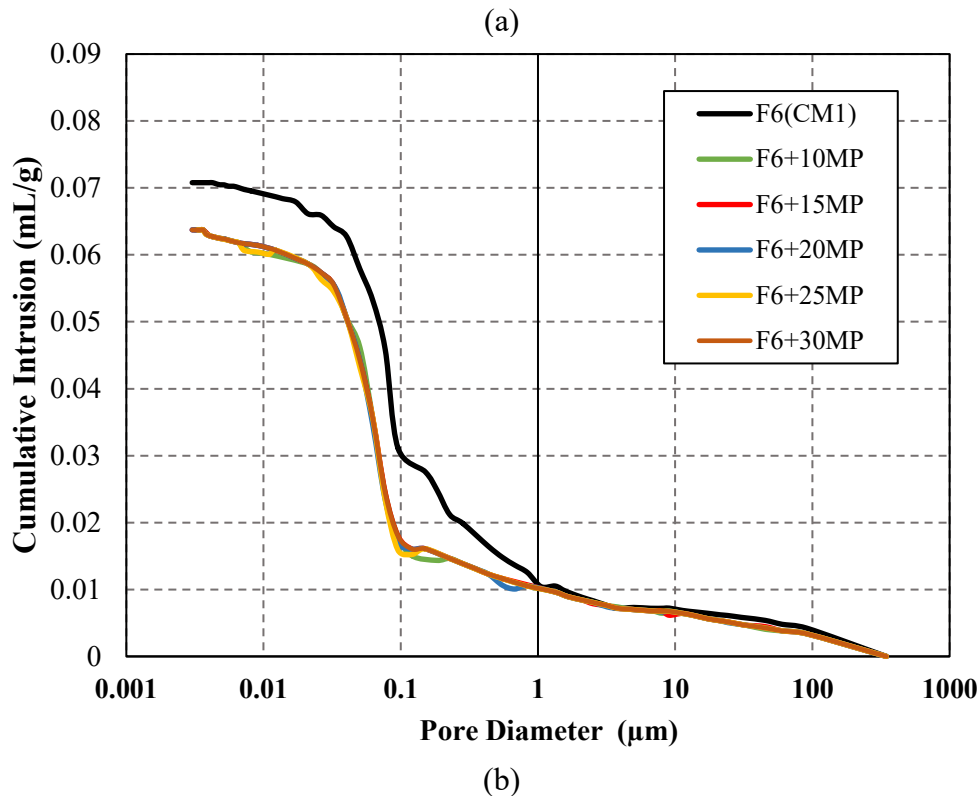


Figure V. 15 Effect of marble powder on (a) porosity and (b) Porosity size distribution

Porosity rates of self-compacting repair mortars are shown in Figure V. 15 (a). The porosity rates average is between 13.8% and 15%. It is clearly seen that the addition of MP lead to a drop in porosity rates. As the amount of MP increases the pore ratio declines slightly. That is may be due to the fact that MP increases the workability of the fresh mortar at lower water content, as a consequence reduces porosity rate. In addition to its filler effect that minimise the voids size. The same conclusion was reported by Can Tombulca and Murat Çavuş [274], they used fly ash as a substitution of lime in lime repair mortars. Other investigations reported that the addition of marble slurry leads to a decline in porosity hence, chloride and water penetration resistance was improved [147,275].

Figure V. 15 (b) illustrates pore size distribution of all samples. It's well noted that two slopes appear in all the graphs, their intersection is a porosity threshold that decreases towards larger pores. The substitution of cement by MP causes an important decline in pore diameter especially micropores finer than 1 µm. However, in the domain of macropores the curves seem almost superimposed.

Bouhamou et al. [69] investigated the use of fine limestone at 20%, 25% and 30% in the formulation of self-compacting concrete and concluded that when the quantity of fine limestone increases, the rate of fine pores decreases. Which leads to a shift in the visible peak towards

smaller sizes, this highlights the effectiveness of fine limestone particles in their role as filler. Similar studies showed that the addition of fine particles allows for a decrease in pore size [276].

V.3.6 Thermal conductivity

The effect of MP on thermal conductivity at 28 days is presented in Figure V. 16. Incorporating MP showed higher conductivity values compared to CM1. Which could be due to the filler effect of MP that leads to less porous matrix. These results are confirmed in the porosity test. We can observe that with the increment of MP, thermal conductivity is reduced gradually but still higher than mortar without MP (CM1).

In general, thermal conductivity of cementitious material ranges from 2 to 2.5 W/m.K [277]. However, the recorded values in this study were placed between 1.9 and 2.1 W/m.K. According to Izaguirre et al. [278] PPF generates improvements in thermal, acoustic and mechanical properties. Other study reported that polypropylene fibre mortars present an increase in thermal conductivity caused by thermal bridging phenomenon [279]. Benchiheub et al. [280] resulted in a decrease about 38% in thermal conductivity when incorporated pozzolana and PPF in lime-based mortars.

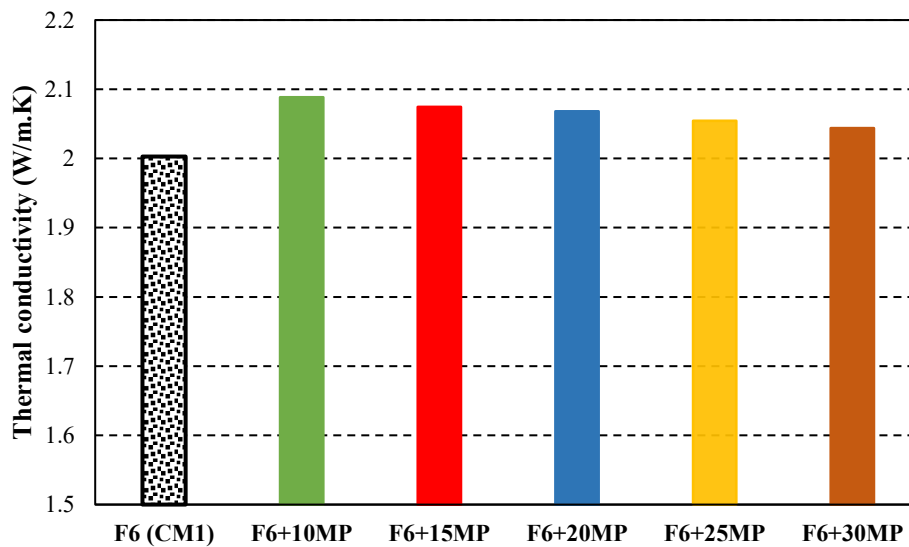


Figure V. 16 Thermal conductivity variation at 28 days

V.3.7 Total free Shrinkage

The total free shrinkage is defined as the synergetic effect of both self-desiccation and autogenous shrinkage which is attributed to water loss and cement hydration. The evolution of total free shrinkage is illustrated in Figure V. 17. In general, shrinkage value of all repair mortars

developed over time and exhibited the same trend in all mixtures. At the first two months, the development was at fast rate then it starts to stabilise with time. This may be related to the cement hydration process. It's well observed that adding marble powder reduces significantly total shrinkage compared to control mortar. 20 % of MP result in higher reduction in total shrinkage value compared to all mixtures. This is due to the decrease in cement content hence decreasing hydration products formation. Comparable results were registered by Li et al. [281], they observed that adding high dosage of limestone powder in ultra-high performance concrete generated lower free shrinkage value. Singh et al. investigated the use of marble slurry on drying shrinkage, and concluded that a decrease in shrinkage value was observed which can be attributed to the fine particles and filler effect of marble slurry that occupy the pores hence restrict the contraction of concrete upon evaporation of excess water. This property of marble slurry to reduce drying shrinkage is very beneficial as it can help in preventing deterioration of concrete and reinforcements from environmental impacts [248].

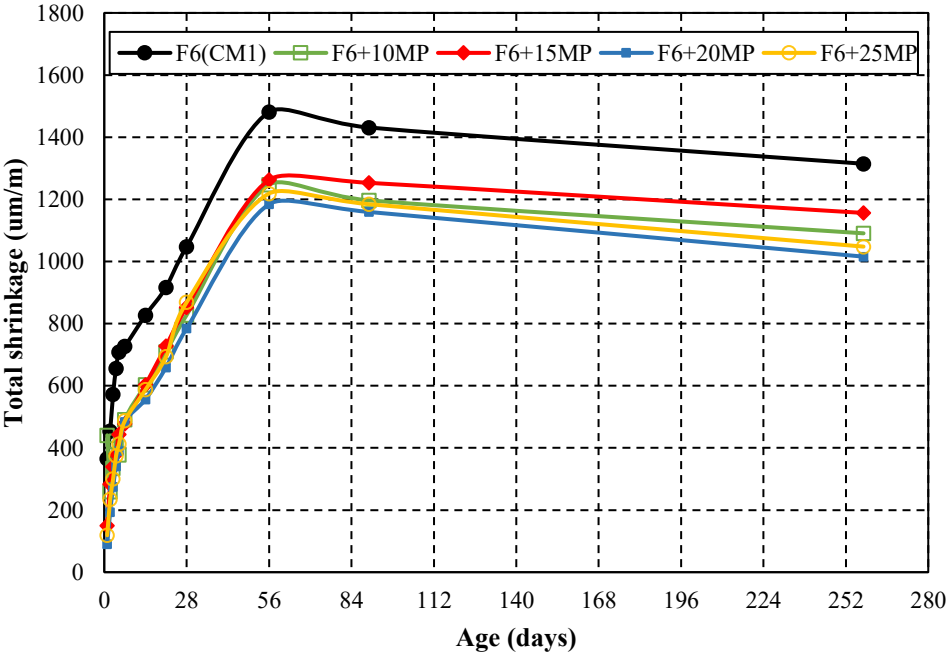


Figure V. 17 Total free shrinkage development

Other researchers investigated the use of waste marble aggregates to replace naturel river sand on drying shrinkage. They resulted in a significant reduction in drying shrinkage of all mixes at all drying durations. The reduction in drying shrinkage with the addition of marble waste aggregates can be attributed to the pore refinement that occurred due to particle shape and pore size distribution of marble waste aggregates [166]. Similar observation of reduced drying

shrinkage in concrete containing marble dust, with a particular physical characteristic, was made by Gameiro et al. [282].

V.4 Effect of hot-dry climate

V.4.1 Adhesion by flexural test

The adhesion strength between self-compacting repair mortar (SCRM) and substrate mortar (SM) was evaluated by flexural bond test in function of marble powder substitution at 7, 28 and 90 days of curing in two conditions (standard and hot-dry climate) (Figure IV. 20.(a)). Figure V. 18 illustrated the effect of MP on bond strength in standard climate. A first analysis shows that flexural bond strength enhanced with age. At an early age (7 days), the enhancement is at high level more than 25% compared to mortar with 0% of MP. The gain in bond strength of F6+10MP, F6+15MP and F6+20MP was in the order of 20%, 20% and 8%, respectively, at 28 days. In the long term (90 days), only F6+10MP and F6+15MP showed an increase in bond strength about 18-20%. Comparable values are obtained in CM1 and F6+20MP. Repair mortars with 25% and 30% MP are characterized with lower bond strength compared to CM1 at 28 and 90 days. The improvement in the adhesion could be explained by the enhancement at the interface between the repair material and the old mortar caused by the increase in the friction between them; due to the angularity shape of the MP (Figure IV. 4.(b)). Similar results were obtained by Benyahia [70] and Aliabdo et al. [283]. Moreover, the fine particles size of marble powder contributes in filling micro voids, thus resulted in denser microstructure. As a consequence, it reduces the porosity and improves the bond strength by enhancing the interface contact.

The obtained bonding results showed that the composite samples exhibited the same failure mode at all ages. Interface damage occurred in all test cases; the SCRM are completely separated from the substrate. Benyahia et al. [284] investigated the adhesion strength using waste glass powder (WGP) at 28 and 56 days. They concluded that using 10% of WGP as cement replacement had good adhesion with the substrate mortar, all the damage occurred in the SM at both ages.

Based on the results presented in Figure V. 18, it can be concluded that using 10%, 15% and 20% of MP are considered as suitable materials for use as cement replacement to produce self-compacting repair mortars.

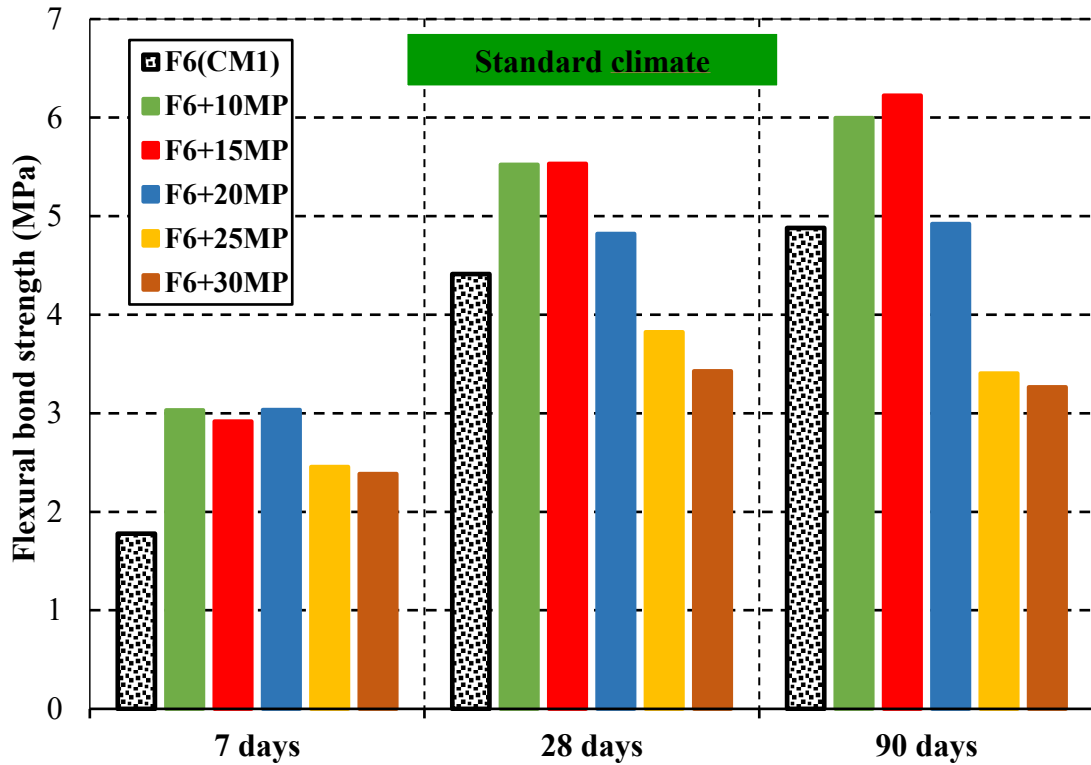


Figure V. 18 Effect of marble powder on flexural bond strength at 7, 28 and 90 days in standard climate

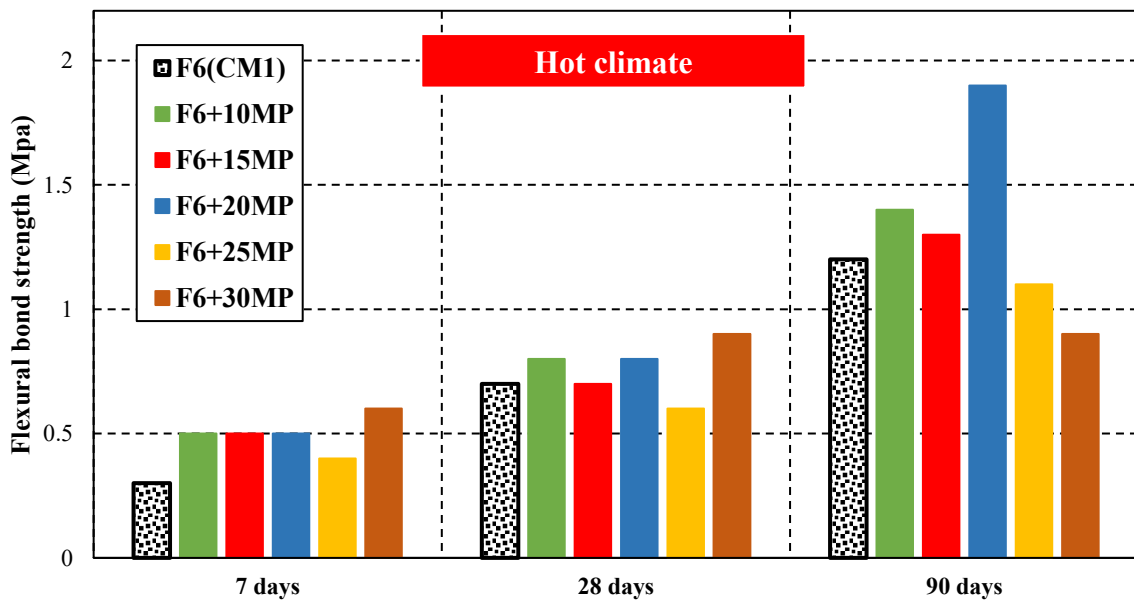


Figure V. 19 Effect of marble powder on flexural bond strength at 7, 28 and 90 days in hot-dry climate

The effect of hot-dry climate on bond strength between repair mortar and substrate mortar in function of marble powder substitution is illustrated in Figure V. 19. The results show that bond strength is enhanced with age of all composites. The incorporation of MP resulted in a slight enhancement in bond strength at all ages. 20% of MP developed the highest bond strength at

longer age. However, it's clearly seen that the high temperature affects negatively the hydration of cement hence the development of bond strength with age compared to standard climate. All composites conserved in hot-dry climate gave bond strength values lower than composites conserved in standard climate. A reduction of about 83%, 84% and 74% is recorded at 7, 28 and 90 days, respectively. This is probably due to uncompleted cement hydration caused by the high-water loss which is required for the hydration.

V.4.2 Adhesion by slant shear test

The durability of reparation depends strongly on the quality of the adhesion. Bond strength between repair mortar (SCRM) and substrate concrete (SC) was evaluated by slant shear test on various composite cylinders specimens (half SCRMs/half SC) at 7, 28 and 90 days conserved in two curing conditions (standard and hot-dry climate). The development in bond strength is illustrated in Figure V. 20 and Figure V. 21 of standard and hot-dry climate, respectively.

A first analysis shows an evolution of slant shear strength in function of age in both conservation conditions. The strength values of cylinder composites conserved in standard and hot-dry climate vary between 5.5-9.2MPa and 4.8- 9.7MPa, respectively.

At early age, all composite specimens conserved in standard climate presented a comparable adhesion strength. It's well known that MP have a beneficial impact on early age mechanical strength thanks to its filling effect which led to minimize micropores. However, at 28 and 90 days we can observe a diminution in strength in composites with MP compared to control composite (F6(CM1)/SC). Which is mainly due to the decline in C_2S and C_3S elements. Benyahia investigated the use of recycled powder (RP) as cement replacement on slant shear bond strength and resulted in a satisfactory finding. The results showed that it is possible to replace the cement up to a rate of 20% RP without compromising the bond strength in the plain water curing environment [190].

On the other hand, a favourable result is obtained by adding MP in composites conserved in hot-dry climate. The result in Figure V. 21 shows that at younger age, MP substitution gives comparable bond strength value as control specimen (F6(CM1)/SC), except for F6+30MP that showed an important strength gain. At 28 days, bond strength increases when MP rises. At later age (90 days), comparable results are obtained in all specimens with increasing MP dosage. Composite with 30% of substitution presents the optimal dosage which gives higher adhesion strength compared to control composite at all ages. Slant shear strength improvement could be due to the high fineness of MP ($5000 \text{ cm}^2/\text{g}$) and its angularity shape (Figure IV. 4.(b)) which

cause an increase in the friction between the repair material and the old concrete and augment the compactness as a consequence, enhance the interface between them [283].

By comparing slant shear strength values of composites conserved in the two different climates, we can observe that the strength of samples cured in standard climates are higher than those cured in hot climate at 3 days. At 28 and 90 days, all composites cured in hot-dry climate and incorporated MP showed bond strength values superior to those cured standard climate. For exception of control composite. Based on the analysis, we can conclude that using MP in repair mortars exposed to hot-dry climate gave a satisfactory performance in terms of bond strength.

Bella et al. recorded that the hydration reactions of cement are thermally activated; i.e., they are accelerated by temperature. Which normally give great resistance, but this is true only at early age [285]. On the other hand, other researchers concluded that long-term strength (28 days) is reduced by accelerated hardening. Probably because the hydration product of concrete which has accelerated hardening is less dense than the hydration products of the concrete in normal temperature ($20 \pm 5 \text{ }^\circ\text{C}$) [286].

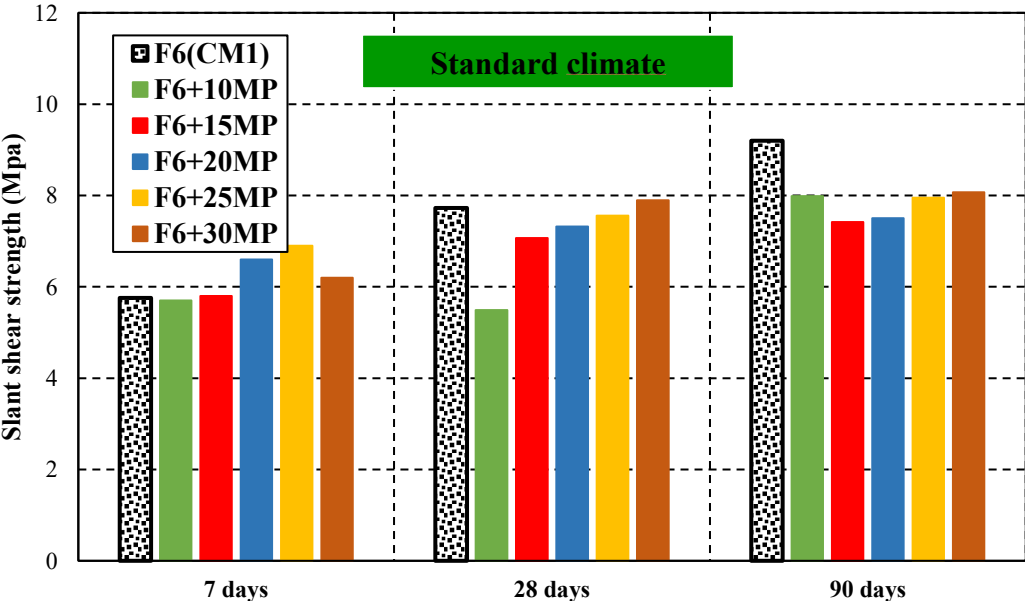


Figure V. 20 Evolution of slant shear strength at 7, 28 and 90 days in standard climate with MP incorporaion

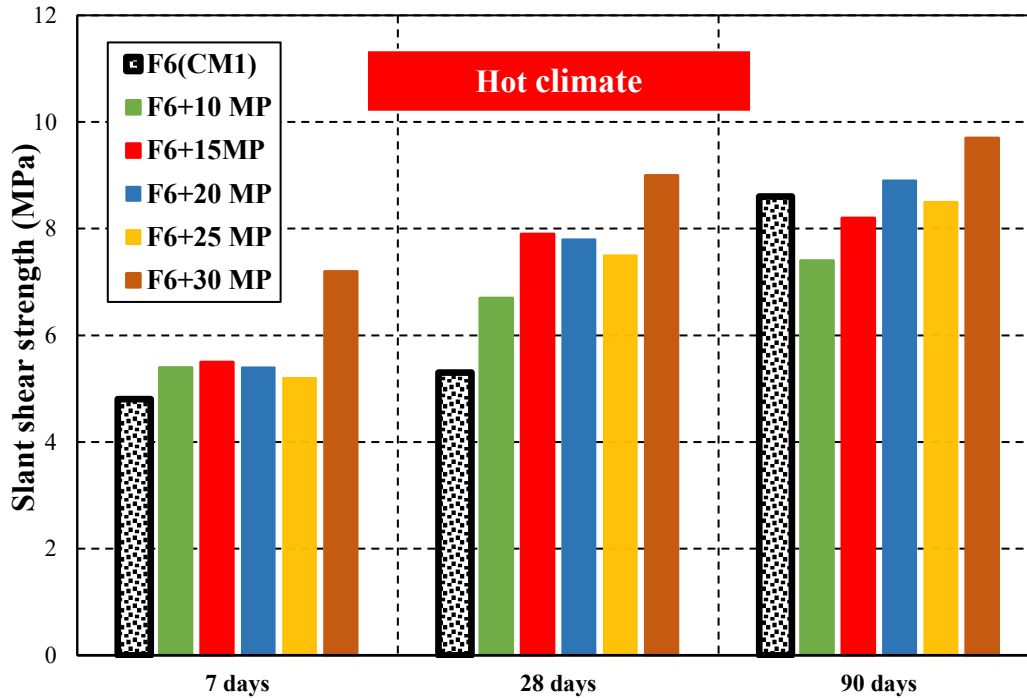
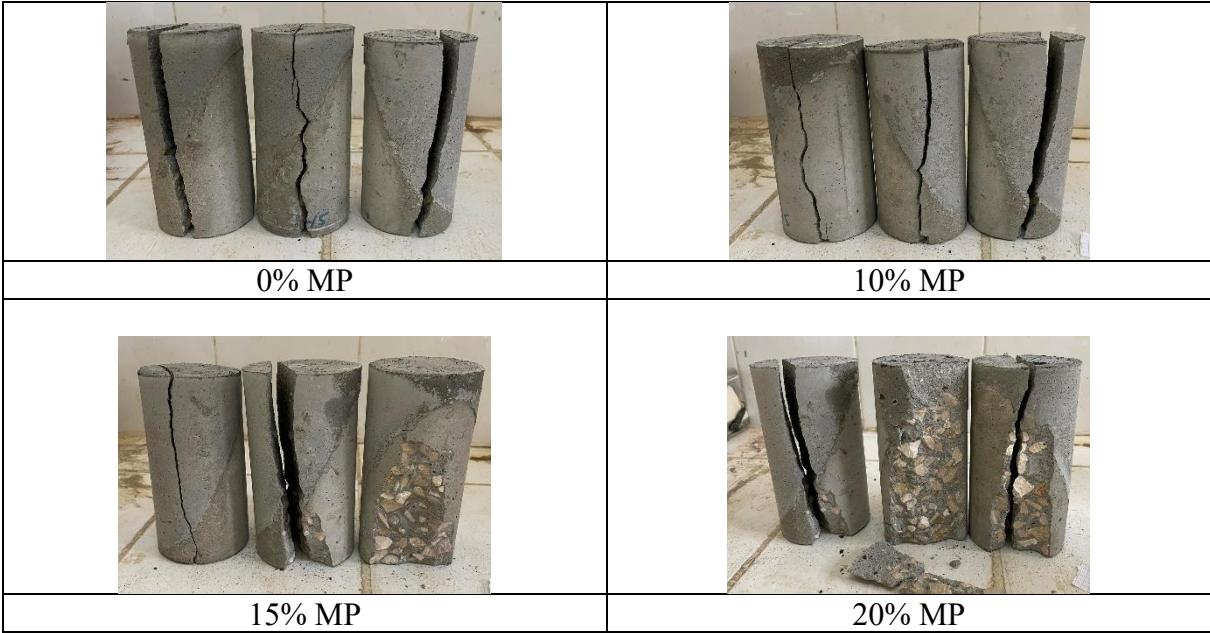
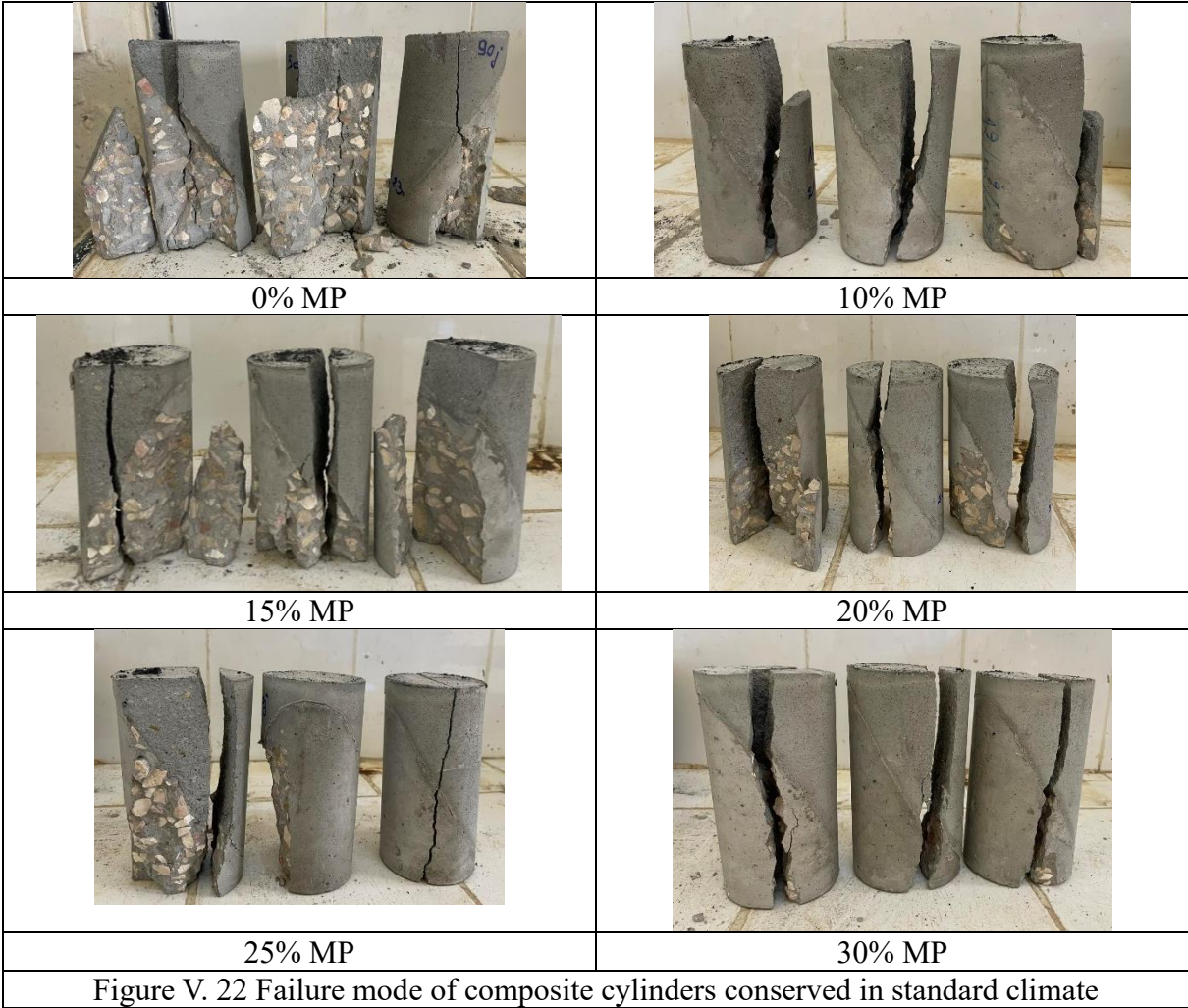


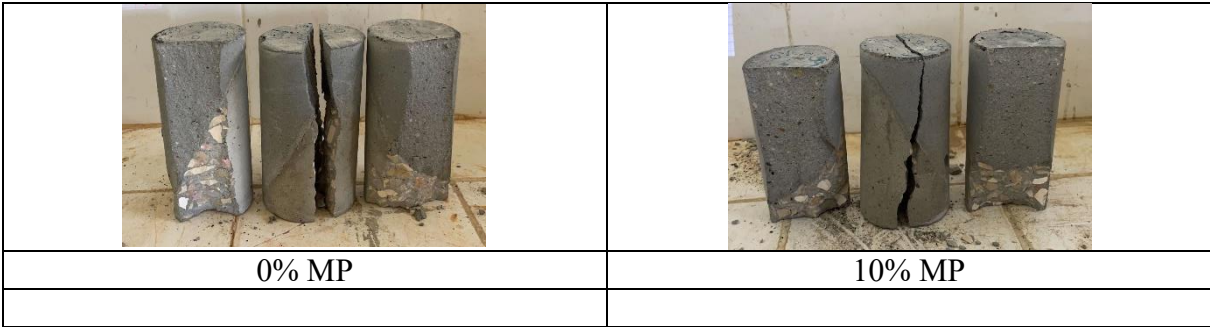
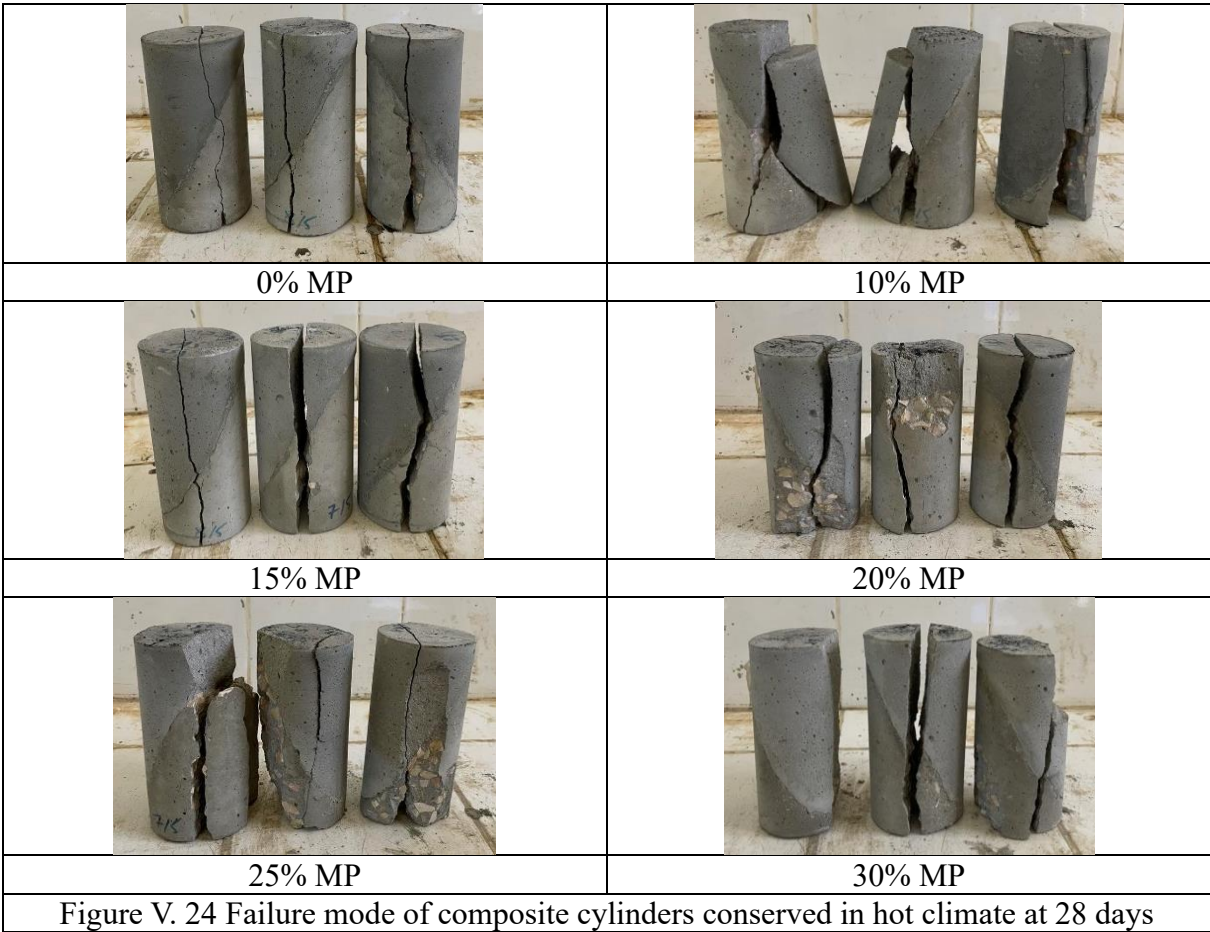
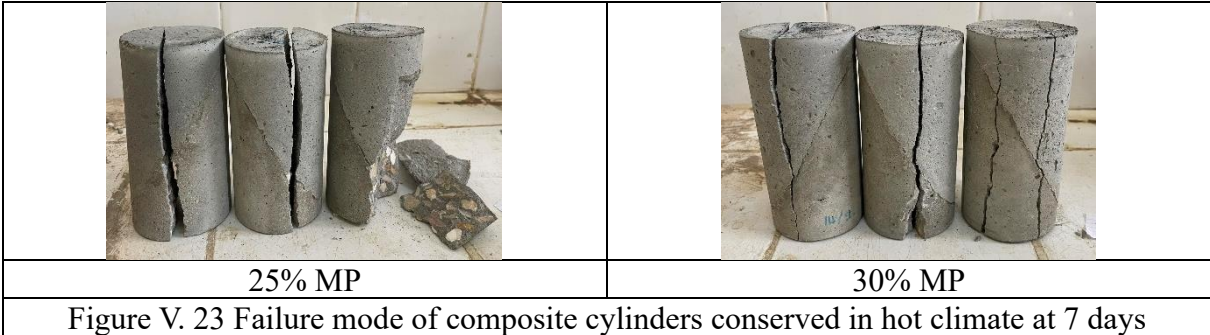
Figure V. 21 Evolution of slant shear strength at 7, 28 and 90 days in hot-dry climate with MP incorporation

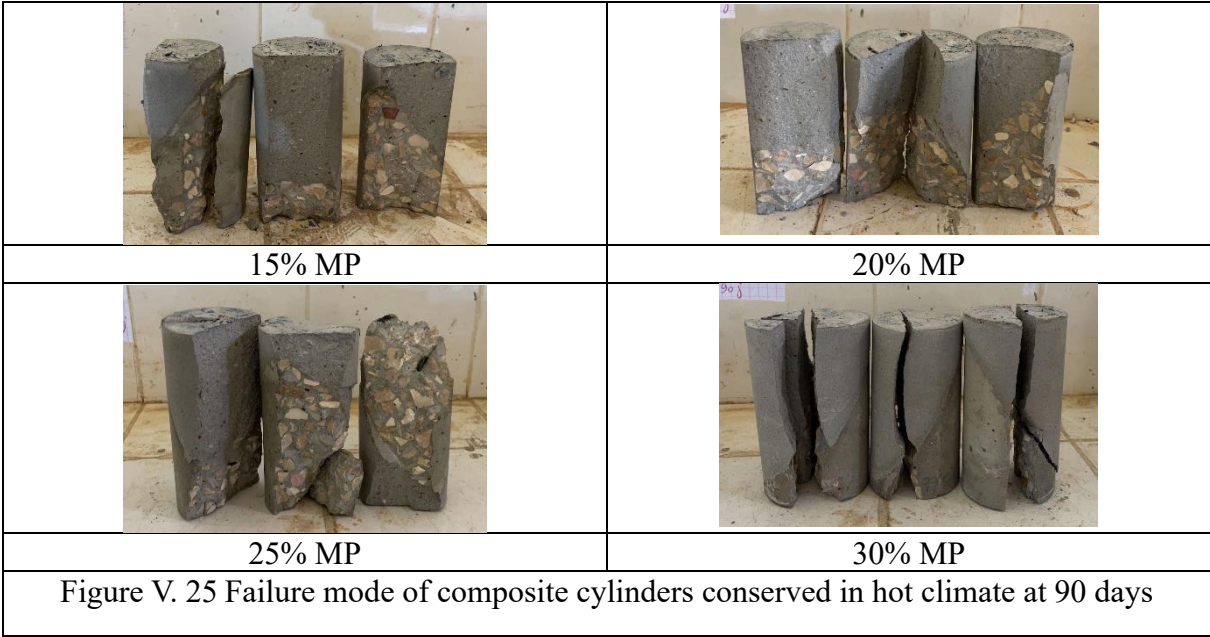
Generally, after 28 days of age, the strength tends to decrease under the effect of hot and dry environment and it stabilizes only after 91 days and even more. The decrease of the strength is due to the water evaporation at early ages that leads to the stop of the reaction of hydration and causes shrinkage cracks [287].

Bendjillali et al. [287] reported that hot climate has a high influence on the development of shrinkage compared to standard climate. Moreover, the incorporation of polypropylene fibres was found to be beneficial in reducing shrinkage evolution in hot environment, where adding 1% of polypropylene fibres reduces shrinkage by half.

Failure mode obtained from slant shear test is depicted in Figure V. 22, Figure V. 23, Figure V. 24 and Figure V. 25. We can distinguish two failure modes, namely adhesive failure (at the interface) or cohesive failure (in repair, in concrete or in both of them). The location of the failure (failure mode) provides valuable information about the quality of the bond between the repair material and the substrate concrete. Generally, if the failure occurs within the substrate, it can be stated that the bond strength is at least as high as that of the substrate concrete. Conversely, if the failure occurs at the bonding interface, the estimated failure strength is equal to the bond strength. Most composite samples showed cohesive failure mode while some others showed fracture in concrete substrates at all ages and in both conditions.







V.4.3 Compatibility

The main objective of this test is to assess compatibility or incompatibility between repair mortar and substrate concrete. The compatibility was evaluated by flexural bond strength in both environment (standard and hot climate) at 7, 28 and 90 days of curing and presented in Figure V. 26 and Figure V. 27, respectively. Three failure modes could be occurred: either cracking that extends through the entire thickness of the repair, delamination at the interface (loss of monolithic behaviour), or failure of the concrete in compression. From the results, it's clear that bond strength increases with age in both environments. However, it decreases by adding marble powder. All bond values vary between 1.5 MPa and 2.6 MPa. Figure V. 28 and Figure V. 29 depict the obtained failure modes of all samples in standard climate and hot climate, respectively. Two failure modes were distinguished in this study. Failure in the middle of the sample (compatible system) was observed in all samples, in both conditions and at all ages. For exception, sample F6+30MP conserved in hot-dry climate showed failure in the extremity of the beam (incompatible system) after 28 days of conservation.

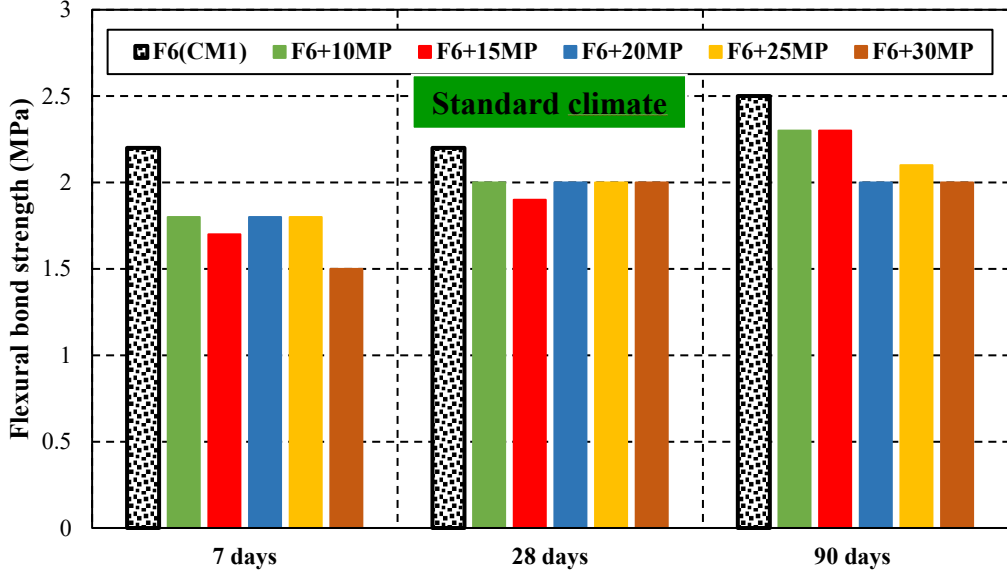


Figure V. 26 Marble powder influence on flexural bond strength at 7, 28 and 90 days in standard climate

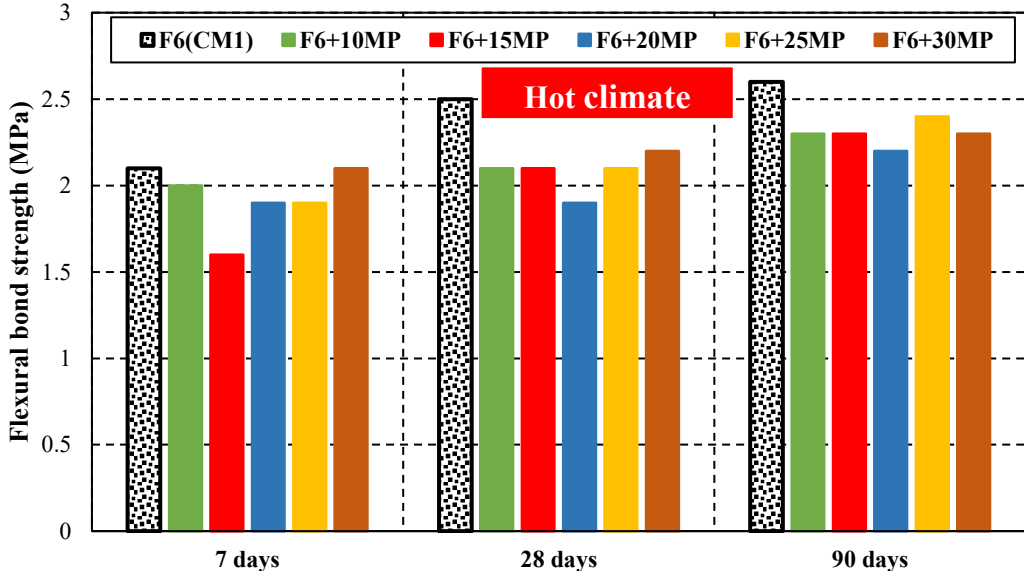
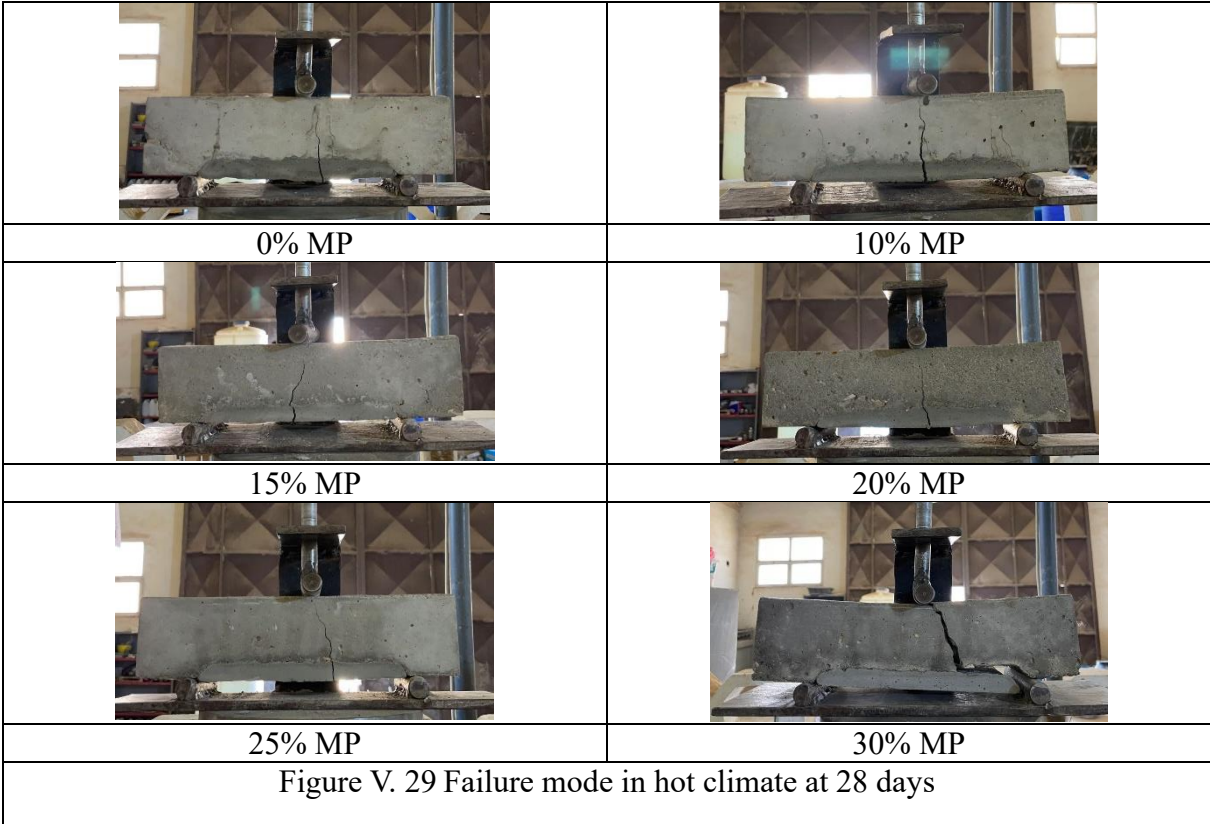
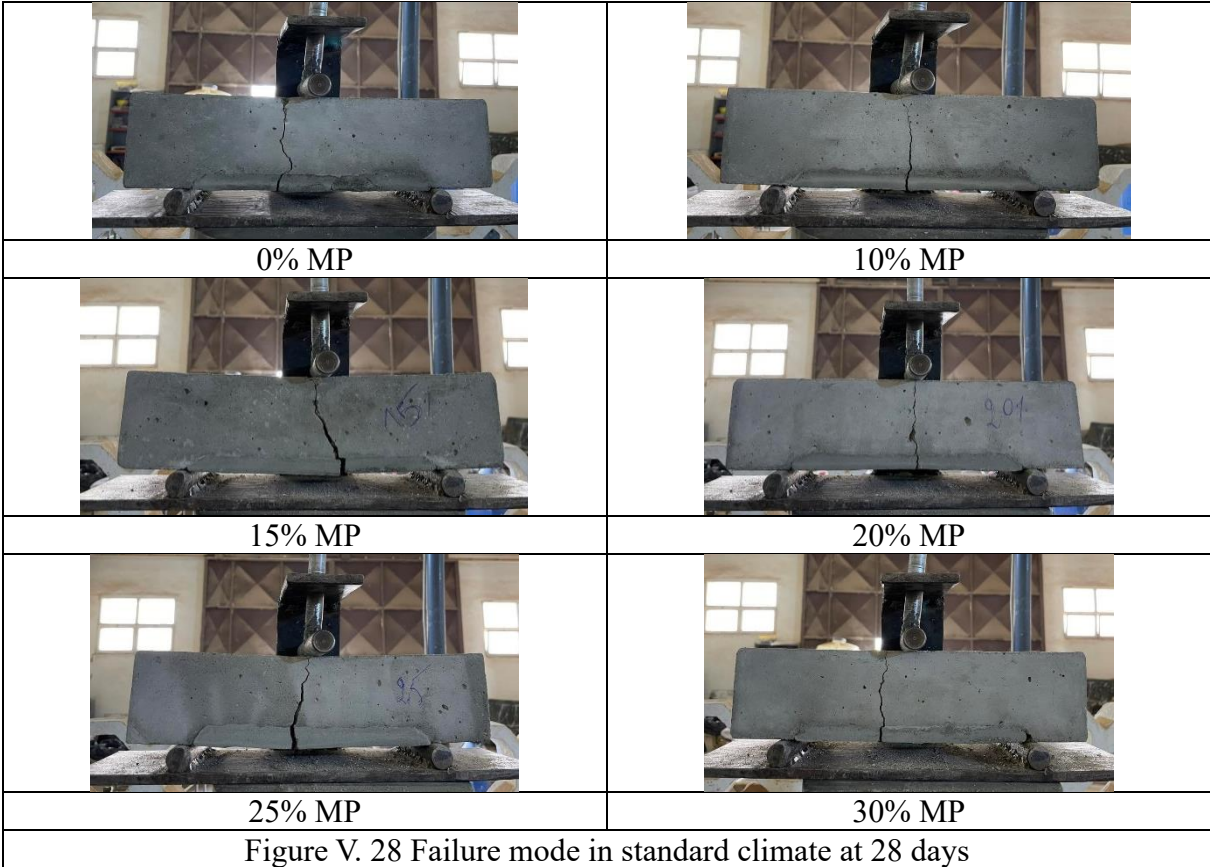


Figure V. 27 Marble powder influence on flexural bond strength at 7, 28 and 90 days in hot climate



V.5 Conclusion

The experimental work was conducted to assess the effect of marble powder as cement replacement on the properties of self-compacting repair mortar reinforced with polypropylene fibres. Precedently, an optimisation of fibre dosage was assessed. Fibre percentage was varied at (0.02%, 0.03%, 0.06%, 0.09% and 0.12%) with maintaining $S_p = 0.6\%$. Then incorporating MP at (10%, 15%, 20%, 25% and 30%) to replace cement. Mortars were evaluated on slump flow, flow time, yield stress, plastic viscosity, fresh bulk density with keeping S_p constant. In addition to mechanical behaviour, elasticity modulus, thermal conductivity, total free shrinkage, water capillary absorption, mercury intrusion porosity with adjusting S_p dosage to maintain slump flow in the range of 25 ± 2 cm and the flow time between 7-11 sec which are required by EFNARC 2005 [61]. The influence of hot climate on adhesion bond strength was also studied, on three adhesion test methods.

The last chapter illustrated results and discussions obtained from the experimental work. The following conclusions are made:

0.06% of polypropylene fibre is the optimal dosage which yields to a good distribution in the matrix, the best workability and rheological properties, the greatest value of compressive strength as well as a good flexural behaviour. The addition of MP to mortar reinforced with 0.06% of PPF decreases yield stress, plastic viscosity and flow time and increases slump flow. In terms of mechanical strength, satisfactory results were obtained by adding up to 20% MP to mortar with 0.06% PPF, it showed a compressive strength comparable to that of mortar with 100% cement. All SCRM found to fulfil the requirements of class R4. An insignificant decrease in Elasticity modulus (E_D) is recorded with the substitution of 10% and 15% of MP. All E_D values were higher than the lower limit (20 GPa) required by the EN 1504-3 Standards for Class R4 repair mortars. The use of marble powder augments significantly the sorptivity coefficient. However, all self-compacting repair mortars satisfy the EFNARC specification, except 20% MP at 28 days. MP was found to reduce significantly total free shrinkage and total porosity by MIP however, led to an augmentation in thermal conductivity. The effect of hot-dry climate is reflected in 70% of drop in flexural bond strength compared to standard climate. MP enhances slant shear bond strength conserved in hot-dry climate; it appears clearly in failure mode that indicates no separation of the combined system.

General conclusion and recommendations

General conclusion

This experimental study was conducted to evaluate the combined effects of marble powder and polypropylene fibres on the behaviour of self-compacting repair mortars. As well as studying the impact of the conservation under a naturally hot- dry climate and standard climate on the durability of repair system. The aim of the work is to produce a self-compacting repair mortar that is economical, environmentally friendly, ductile and durable, by utilizing marble powder, which are readily available throughout our country.

The experimental program was primarily focused, in a first phase, on the optimisation of polypropylene fibre dosage carried out at fresh and hardened states. After that, the substitution of cement by marble powder is carried out. Repair mortars were evaluated on workability, rheology, mechanical behaviour, elasticity modulus, thermal behaviour, water capillary absorption, shrinkage and mercury intrusion porosity (MIP). The effect of hot climate on adhesion bond strength was also assessed on composite specimens (half repair material/ half substrate material).

The main conclusion could be summarized in the following points:

- Introducing PPF at low dosages (0.02% and 0.03%) showed a positive influence on both workability and rheological parameters. Nevertheless, adding higher percentages (0.06% and 0.09%) led to decrease the fresh properties. 0.12% of PPF showed fibre agglomeration which causes a drop in yield stress and plastic viscosity.
- The optimal fibre dosage is 0.06%, which yields to the greatest value of compressive strength, a good flexural behaviour and a good distribution in the matrix.
- The combination of PPF and MP decreases yield stress, plastic viscosity and flow time and increases slump flow.
- Incorporating MP in self-compacting repair mortar to replace cement results in a reduction in fresh bulk density, as MP have lower specific density than cement.
- Flexural strength is directly influenced by introducing fibres, it increases with the increment of fibre percentage. In compressive strength, mortar with 0.06% PPF exhibited the highest compressive strength of 72 MPa which recorded to the optimal dosage.
- Satisfactory findings were obtained by adding up to 20% MP to mortar with 0.06% PPF, it resulted in compressive strength comparable to that of mortar with 100% cement. All SCRM's found to fulfil the requirements of class R4.

General conclusion and recommendations

- Elasticity modulus (E_D) results reveal that 10% and 15% of MP substitution showed insignificant decrease in the E_D . From 20% an important diminution is obtained at all ages. Besides, a very good relationship is obtained between compressive strength and flexural strength, between elasticity modulus and compressive strength and between elasticity modulus and sorptivity coefficient.
- The use of marble powder augments significantly the sorptivity coefficient at 28 and 90 days. However, all self-compacting repair mortars satisfy the EFNARC specification, except F6+20MP at 28 days.
- According to thermal conductivity results, adding MP led to an augmentation in thermal parameter compared to control mortar F6(CM1).
- From the MIP, mortars incorporated MP showed a decreased porosity compared to control mortar F6(CM1). The influence of MP is more apparent at micro pore level (less than 1 μm). While at higher pore size the graphs seem to be superposed and the effect is lower.
- MP was found to reduce significantly total free shrinkage. Mortar F6+20MP showed the minimal shrinkage value.
- Adhesion strength by flexural test showed that using up to 20% of MP in repair mortars enhance bonding strength due to the fine particle size of MP and its contribution in filling the microvoids, enhancing the compactness of the mixture and thus enhancing the interface contact between repair mortars and the old mortar. All composite samples exhibited the same failure mode at all ages. Interface damage occurred in all test cases; the SCRM are completely separated from the substrate in both curing conditions.
- Hot-dry conservation affects negatively flexural bond strength values; it declines at all ages by more than 70% compared to standard climate.
- Slant shear strength test showed that MP enhances bonding strength between repair materials and substrate concrete conserved in hot-dry climate, which appears clearly in failure mode that occurs in the composite and indicates no separation of the combined system. Nevertheless, the effect of MP on composites conserved in standard climate is unfavourable, especially at long term.
- Substantial differences in the failure stresses of the uniaxial tension and slant shear test methods were attributed to their different geometries and loading conditions.
- Compatibility test results showed a compatible reparation using MP as cement replacement in two curing conditions. An exception for composite with 30% MP that showed incompatibility in hot-dry climate conservation.

General conclusion and recommendations

- The synergistic work of MP and PPF revealed in appreciable results for self-compacting repair mortar performance that cannot be achieved if they were used separately.

In general, the current research focuses on the utilization of the marble powder to replace cement in self-compacting repair mortar reinforced with PPF fibre in accordance with the international standard specifications and satisfactory results were obtained.

General conclusion and recommendations

Recommendations

In order to confirm and deepen the results of this work, it would be interesting to continue this study by focusing on two themes:

- In the work we presented, we focused on the formulation and characterization of self-compacting mortars with a single type of fibres. It would be preferable to reformulate the mixes using a combination of fibres of different types and lengths.
- In the formulation of self-compacting repair mortars, we incorporated marble powder as a cement replacement. It is recommended to use two types of supplementary cementitious materials (one active and one inert) in a ternary formulation.

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Annexes

Annexe (A) Meteorological Data of the Wilaya of Laghouat

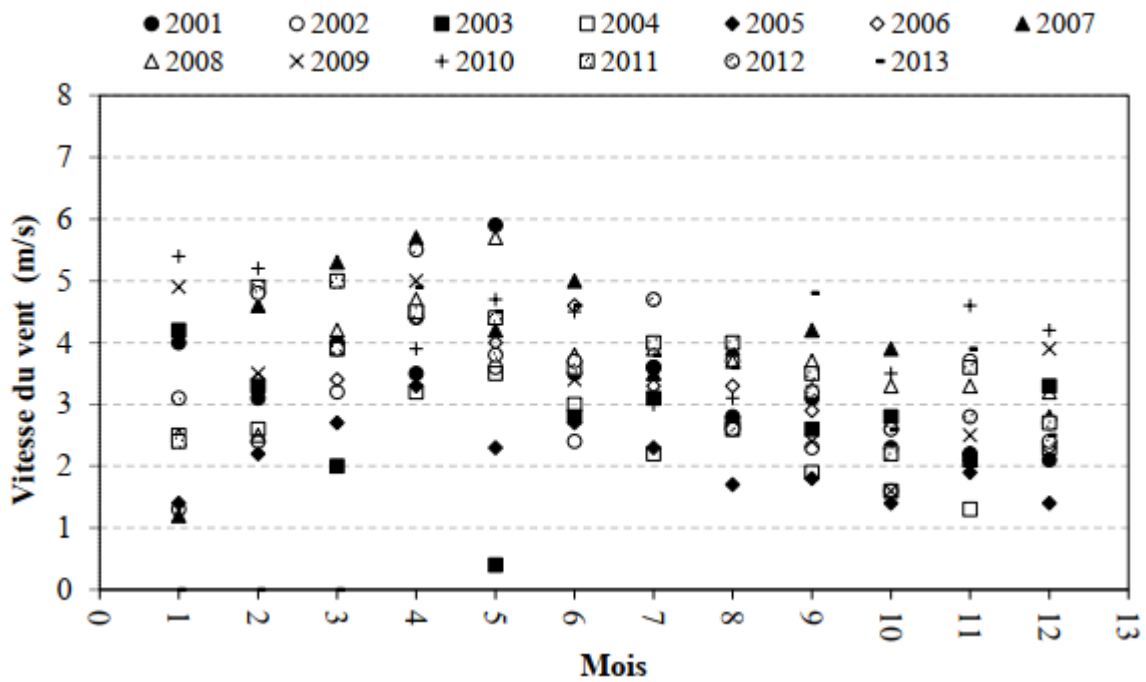


Figure.A.1 Monthly variation of wind speed between 2001 and 2013

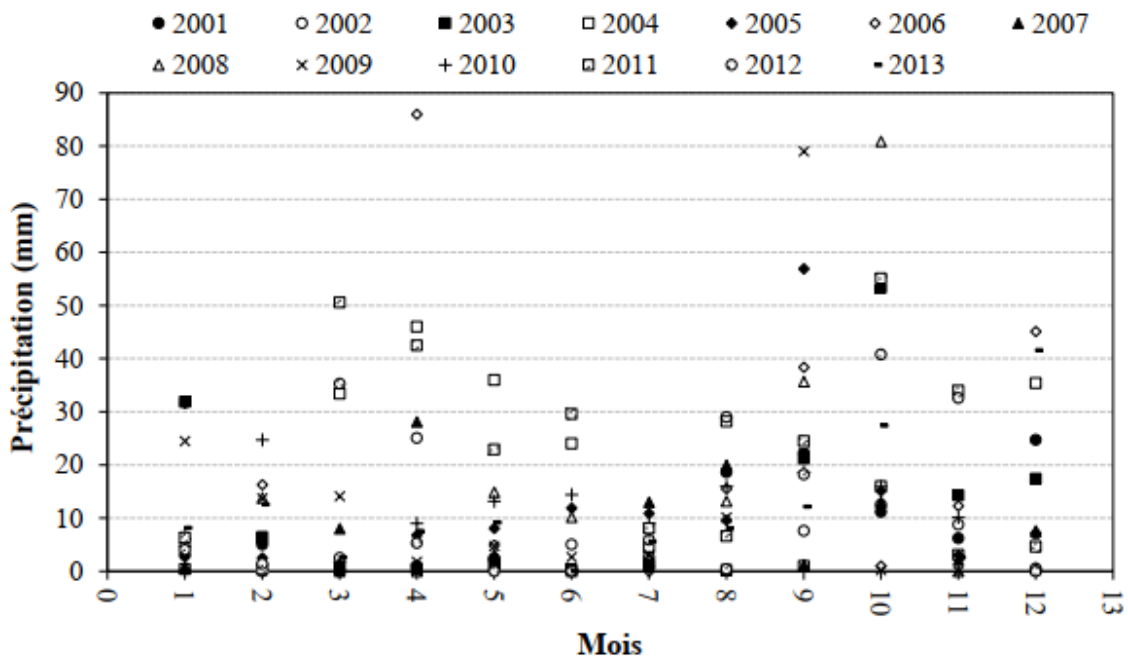


Figure.A.2 Monthly variation of precipitation between 2001 and 2013

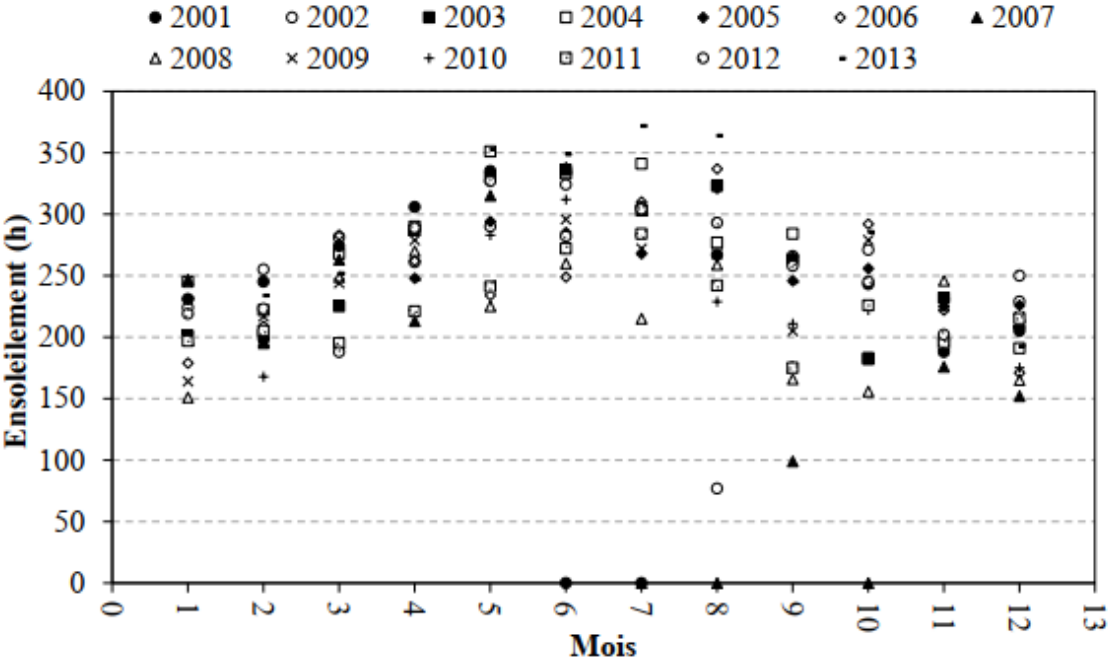


Figure.A.3 Monthly variation in solar exposure between 2001 and 2013

Annexe (B) technical data sheet

NOTICE TECHNIQUE

Version 03

Edition février 2017

2

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1

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MEDAFLOW 30

Conforme à la norme NA 774 , NA 5102 et NA 5075

Super plastifiant-haut réducteur d'eau**Description**

Le **MEDAFLOW 30** est un super plastifiant haut réducteur d'eau de la troisième génération. Il est conçu à base de Polycarboxylates d'Ether qui améliore considérablement les propriétés des bétons.

Le **MEDAFLOW 30** permet d'obtenir des bétons et mortiers de très haute qualité.

En plus de sa fonction principale de super plastifiant, il permet sans modifier la consistance, de réduire fortement la teneur en eau du béton.

Le **MEDAFLOW 30** ne présente pas d'effet de retard de prise.

Domaines D'application

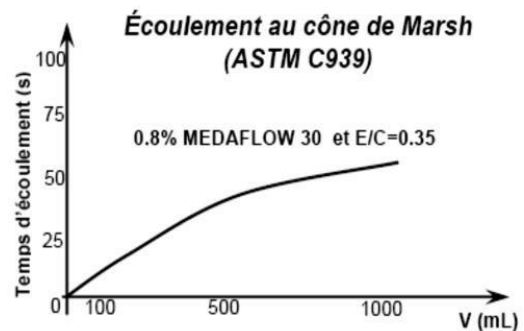
- Les bétons de préfabrication.
- Les bétons prêts à l'emploi.
- Les bétons lourds et légers.
- Les bétons d'ouvrages d'art.
- Les bétons de dallages industriels.
- Les bétons de bâtiment.
- Les bétons précontraints.
- Les bétons pompés.
- Les bétons pour fondations profondes.
- Les bétons pour ouvrages fortement ferrillés.
- Les bétons soumis à des milieux agressifs.
- Les BHP, BTHP, BUHP et BFUP
- Les bétons autonivelants - bétons autoplaçants.
- Les bétons architectoniques.

Propriétés

Grâce à ses propriétés le **MEDAFLOW 30** permet :

Sur béton frais :

- Obtention d'un rapport E/C très faible
- Amélioration considérable de la fluidité
- Une très bonne maniabilité
- Éviter la ségrégation
- Faciliter la mise en œuvre du béton

**Sur béton durci :**

- Augmenter les résistances mécaniques à jeune âge et à long terme (voir tableau).
- Diminuer la porosité
- Augmenter la durabilité
- Diminuer le retrait et le risque de fissuration

Désignation	Rc (MPa)		
	3J	7J	28J
MEDAFLOW 30 (1.4%)	39.2	54.7	62.2

Caractéristique

- Aspect..... Liquide
- Couleur..... Brun clair
- pH..... 6 – 6,5
- Densité 1, 07 ± 0,01
- Teneur en chlore..... < 0,1 g/l
- Extrait sec 30%

Les renseignements donnés dans cette notice sont basés sur notre connaissance et notre expérience à ce jour. Il est recommandée de procéder à des essais de convenue pour déterminer la fourchette d'utilisation tenant compte des conditions réelles de chantier.



Zone industrielle Oued Smar – BP85 Oued Smar – 16270 Alger

Tél : (213) 021 51 66 81 & 82

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www.granitex.dz - E-mail: granitex@granitex.dz



MEDAFLOW 30

Conforme à la norme NA 774 , NA 5102 et NA 5075

Super plastifiant-haut réducteur d'eau

Mode D'emploi

Le **MEDAFLOW 30** ne doit pas être ajouté directement dans l'eau de gâchage, mais après un temps préalable de malaxage et après que 50 à 70% de l'eau de gâchage ait été ajoutée.

Le **MEDAFLOW 30** peut être aussi ajouté directement dans le camion malaxeur (toupie), et après introduction de la dose convenable, le malaxeur devra tourner à grande vitesse pendant 2 à 3 minutes après l'introduction du super plastifiant ;

Il est conseillé d'ajouter le **MEDAFLOW 30** à un béton qui ne soit pas trop ferme

Dosage :

Plage de dosage recommandée :

0,5 à 2,0 % du poids de ciment soit 0,46 à 1,85 litre pour 100 Kg de ciment.

Le dosage optimal doit être déterminé sur chantier en fonction du type de béton et des effets recherchés

Conditionnement Et Stockage

Le **MEDAFLOW 30** est conditionné en bidons de 10Kg, fûts de 210 Kg et 240 Kg, cubique 1100kg.

Délai de conservation :

Une année dans son emballage d'origine, à l'abri du gel et de la chaleur ($5^{\circ}\text{C} < t < 35^{\circ}\text{C}$).

Lors d'une exposition du produit au soleil, sa couleur est sujette à changer de ton.

Précautions D'emploi

Manipulation non dangereuse.

Se référer à la Fiche de Données de Sécurité disponible sur : www.granitex-dz.com

NB : La couleur des produits à base de Polycarboxylates d'Ether (PCE) lors d'une exposition aux UV, est sujette à changer de ton , mais qui n' a aucune incidence sur les propriétés et les effets de l'adjuvant.

PV d'essais conforme aux normes, établi par le

CNERIB en 22 AVR 2012

Les renseignements donnés dans cette notice sont basés sur notre connaissance et notre expérience à ce jour. Il est recommandée de procéder à des essais de convenance pour déterminer la fourchette d'utilisation tenant compte des conditions réelles de chantier.



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Annexe (C) Excel sheet providing the composition of self-compacting mortar

Excel sheet providing the composition of self-compacting mortar

Essais sur Mortier

Entrer data dans cellules en rouge

Valeurs calculées dans cellules en noir

Référence du mélange

Essai N°

CEM I 52,5 +

Date 03/05/2025

0 % de Poudre de marbre (PM)

volume de mortier (litres)

1000.00

sable/mortier vol

0.45

E/P par vol.

0.91

poudre vol (%)

28.796

Eau volume (%)

26.204

composition Poudre(vol %)

type

ciment portland

100

Poudre de Marbre

0

superplast - MEDAFLOW30

0.9

% (Sp/P)

Densité relative

3.03

teneur en eau du sable

	humidité (%ab)	absorption(%)	correction (%)
poids humide (gms)	200	0.00	0.58
poids sec (gms)	200		

Materiaux	Volume	Densité	Masse	Contenance d'eau		poids mélange	
	litres	kg/m ³	kg	%	kg	kg	
poudre	287.958	3030	872.513			872.513	
Ciment	287.958	3030	872.513			872.513	
PM	0.000	2620	0.000			0.000	
Eau (70%)	262.042	1000	262.0			263.331	W1 184.332
Eau (30%)							W2 78.999
superplastifiant MEDAFLOW 30		1070	7.85	70	5.497	7.853	
Sable	450.000	2600	1170.000	-0.58	-6.786	1170.000	
Total	1000.000					2313.697	

E/P poids = 0.300

1		poids mélange	
Volume (ℓ)		g	
poudre		872.513	
Ciment	0.288	872.51	
PM	0.000	0.00	
Eau	0.262	263.33	W1 184.3
	E theorique	262.04	W2 79.0
superplastifiant MEDAFLOW 30		7.85	
Sable	0.4500	1170.0	
Total	1.0000	2313.7	

Annexe (D) Technical data sheet of polypropylene fibres


better together

Duomix® M12

FICHE TECHNIQUE

Performances

Propriétés du matériau

Matière première	Polypropylène vierge, monofilament
<i>Valeurs nominales</i>	
Résistance à la traction	260 N/mm ²
Point de fusion	165°C
Densité du matériau	0,91 kg/dm ³

Propriétés de la fibre

Longueur: 12 mm



Densité linéaire: 7,5 dtex
(Diamètre: 32 µm)



Effet réseau

Surface spécifique: 135 m²/kg
110.000.000 Fibres/kg

Safety



Certificats du produit



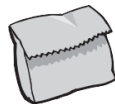
Conformité du produit

Duomix® est conforme aux normes EN 14889-2

Certificats du système



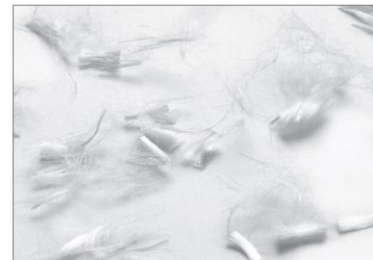
Emballage



g/sac: 600-900-1000
sacs/boîte: 30 - 20 - 20
boîtes/palette: 25 - 25 - 30
kg/palette: 450 - 450 - 600

Les fibres sont emballées par 600-900-1000 g dans des sacs dégradables dans l'eau

Stockage



DUOMIX® M12

LA SOLUTION POUR LE CONTRÔLE DE LA FISSURATION DUE AU RETRAIT PLASTIQUE

Les fibres synthétiques Duomix® réduisent les fissurations lors du retrait plastique et diminuent le ressuage.

ASSISTANCE POUR LA FORMULATION DES BÉTONS FIBRÉS

Vous pouvez compter sur notre support à n'importe quel étape de votre projet, depuis la conception jusqu'à l'assistance chantier. Nos services incluent les recommandations sur la réalisation des bétons, les détails constructifs, l'optimisation de la formule béton et le total contrôle des procédures de qualité. Nous sommes également heureux de partager nos connaissances avec vous et votre équipe. N'hésitez pas à nous contacter pour organiser une présentation ou une formation chez vous, au sujet des fibres métalliques et des synthétiques.

Consultez www.bekaert.com/dosingdramix pour connaître nos recommandations relatives à la manipulation, au dosage et au malaxage. Tous les autres documents spécifiques et certificats figurent sur le site www.bekaert.com/dramix/downloads.

Annexe (E) Specimen's preparation, conservation and failure mode



