THE USE OF WASTE WOOD IN CEMENT MORTARS

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ABSTRACT

The use of waste wood in cement mortars

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It is a well-known fact that CO_2 emission generated during cement manufacturing is threatening the global pollution. Since concrete is the second most consumed substance on Earth after water, it is not surprising that a cement industry accounts for around 5 percent of global carbon dioxide emissions itself. Generation of all kinds of wastes is another alarming matter in terms of the environment and health. This study addresses the influence of the use of wood waste on the fresh and hardened properties of cement mortars. Wood wastes used in this study were in the form of wood powder and wood fibre. Wood powder and wood fibre were used as partially replacement materials both in cement and sand at the replacement levels of 1%, 2%, 3%, 4% and 5%. Physical characterisation namely X-Ray Fluorescence as well as particle size distribution were performed in this thesis. Mechanical properties such as compressive and flexural strength as well as porosity and permeability of cement mortars combined wood wastes were measured. Resistance to freeze and thaw of these mortars are also examined in the thesis. Experimental results have shown that inclusion of wood wastes in cement mortars enhances the mechanical properties of these mortars. Durability characteristics of these mortars were also found to be improved when wood waste is used as substitution material. Combining waste wood in cement mortars have also found to positively influence the cost efficiency of these mortars. The results reported in the thesis do

not only provide a more sustainable development of cement-based materials for construction practices but also suggest an approach for the waste management scheme to be recognised particularly for the undeveloped countries.

Keywords: Waste wood, mechanical properties, durability characteristics, cement mortars

ÖZ

Çimento harçlarında atık ahşap kullanımı

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Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri

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Çimento üretimi sırasında oluşan CO_2 emisyonunun küresel kirliliği tehdit ettiği iyi bilinen bir gerçektir. Beton, sudan sonra Dünya'da en çok tüketilen ikinci madde olduğundan, bir çimento endüstrisinin küresel karbondioksit emisyonlarının yaklaşık yüzde 5'ini oluşturması şaşırtıcı değildir. Her türlü atığın üretilmesi çevre ve sağlık açısından endişe yaratan bir diğer konudur. Bu çalışma, ahşap atığı kullanımının çimento harçlarının taze ve sertleştirilmiş özellikleri üzerindeki etkisini ele almaktadır. Bu çalışmada kullanılan ahşap atıkları ahşap tozu ve ahşap lifi şeklindedir. Basınç dayanımı ve eğilme mukavemeti gibi mekanik özellikler ile ahşap atıklarının katıldığı çimento harçlarının gözenekliliği ve geçirgenliği ölçülmüştür. Bu harçların donma ve çözülmeye karşı direnci de incelenmiştir. Deneysel sonuçlar, ahşap atıklarının çimento harçlarına katılmasının bu harçların mekanik özelliklerini arttırdığını göstermiştir. Bu harçların durabilite özelliklerinin, ahşap atığı ikame malzemesi olarak kullanıldığında da iyileştirildiği bulunmuştur. Fiziksel karakterizasyon için X ışınları flor ışıması ve parçacık boyut analizleri yapılmıştır. Atık ahşabın çimento harçlarına dahil edilmesinin de bu harçların maliyet etkinliğini olumlu etkilediği bulunmuştur. Tezde bildirilen sonuçlar, inşaat uygulamaları için sadece çimento bazlı malzemelerin daha sürdürülebilir bir gelişimini sağlamakla kalmayıp, aynı zamanda atık yönetimi planının özellikle gelişmemiş ülkeler için tanınması için bir yaklaşım önermektedir.

Anahtar Kelimeler: Ahşap atığı, mekanik özellikler, durabilite, çimento harcı

To my precious family

For their infinite support, trust and motivation

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CHAPTER I

INTRODUCTION

1.1 Sustainable assessment of construction industry and waste generation

The use of cement, particularity for making concrete is increasing every year. It is a well-known fact that the cement manufacturing is an energy and carbon dioxide intensive process. In order to produce one tone of cement, one tone of carbon dioxide is being emitted to the atmosphere. Perhaps, there are other alternative binders such as lime and gypsum however, the use of those as a binder material in constructions brings many complications with itself. Lime for instance is a very water retaining binder. This means that the workability of lime is not attained easily. Fresh state properties of these binders are not the only problems. For example, lime has got very low strength and high porosity. This brings a great barrier for this material to be used in construction practice. Of course these negations could be enhanced using pozzolanic materials or some mineral admixtures however, the load bearing capacity of lime still would not be comparable to cement. The use of gypsum on the other hand makes a very sticky mixture at the freshly mixed state. This problem can be solved using or increasing the sand content in the mixture but then alters the hardened state properties of these mixture afterwards.

The main message that the author wants to convey is that replacing cement with another binder material is not an easy task. On the other hand, the waste generation due to industrial production is another alarming matter of the planet. These issues are more alarming particularly at developing countries where the waste management systems are not often developed.

Even if the waste management options are well conducted, using these alternatives can be more critical. For instance, incineration causes carbon dioxide emissions and landfilling can also create soil and water contamination at the long-term. In this thesis, the waste wood is proposed to be used as substitution material in cement mortars. Waste wood is used in the form of wood powder and wood fibre. The waste wood is used both as a cement and sand substitute.

The use of waste wood both as a cement and a sand substitute in making mortars first of all suggest a reduction amount of the raw materials for the process. The reduction in the cement consumption brings many advantages as the manufacturing process of this binder is carbon and energy intensive. Using the waste wood as a substitution material to sand also suggest reserving the natural resources as well as saves the energy required to extract and grind the rocks into required size for mortar making.

1.2 Objectives of the thesis

Objectives of the thesis are listed herein:

- Characterisation of the waste wood materials
- Characterisation of the wood powder and wood fibre
- Obtaining a suitable mix design for cement mortars
- Establishing a mix design principle for the inclusion of waste wood
- Combining the wood powder and wood fibres in mortars both as a binder and sand substitution
- Measurement of the fresh properties for cement mortars combining waste wood
- Measurement of physical properties of cement mortars combining waste wood
- Measurement of mechanical properties of cement mortars combining waste wood

- Measurement of durability properties of cement mortars combining waste wood

1.3 Structure of the thesis

Thesis begins with an introduction to address the main research area as well as the objective of this study. The thesis is then reporting a detailed literature survey study to address the consumption and manufacture of cement as well as the waste generation and particularly the waste wood inclusion in cement-based materials in Chapter II. Previous studies that focused on the inclusion of waste wood in cement based materials are summarised. The materials used for the experimental part of this thesis are provided in Chapter III whereas the standard experimental procedures are reported in Chapter IV. Experimental results and discussions of cement mortars combining waste wood are noted in Chapter V. Chapter VI concludes the thesis and suggest future work within the research area.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter begins with the enlightenment of the use and manufacturing process of cement. It is then addressing the need for the alternative substitution materials for cement and hence the chapter is then reporting the waste materials used in construction practice as a substitution material to binders. The description and the classification of waste in North Cyprus are then reported. Chemical and physical properties and therefore the suitability of the waste wood in cement based materials are then investigated in this chapter. Mechanical properties and durability characteristic of mortars combined waste wood are then reported in detail.

2.2 Portland Cement

2.2.1 The global use of cement

For construction applications, Portland cement is one of the most important hydraulic binding materials that are produced by mixing the clinker and very few amount of gypsum. Clinker is formed by heating the calcareous and clayey raw materials in a kiln. The final product has a greyish colour because of the iron oxide and manganese that exist in the raw materials of PC (Erdoğan, 2016).

The production of Portland cement requires high level of energy and causes considerable amount of carbon dioxide emission to the atmosphere. 5% of global CO_2 emissions, in other words 222 kg of CO_2 per ton of Portland cement, can be related with the manufacture of Portland cement (Paris et al., 2016).

2.2.2 Manufacturing of Portland cement

Manufacturing of Portland cement (PC) starts with the production of clinker. Clinker can be produced by heating the mix of calcareous and clayey materials to high temperatures (1350-1450^{0}C). After clinker cooled to air temperature, 3%-6% of $CaSO_4.2H_2O$ (gypsum) is added to the clinker and mixed (Erdoğan, 2016). The concluded reaction is:

$$\text{Clinker + Gypsum (3\%-6\%)} \longrightarrow \text{Portland cement}$$

2.2.3 Components of Portland cement

2.2.3.1 Oxide composition of Portland cement

Cement chemists used only one letter for the symbols of components in Portland cement. The components and their amount in PC are shown in Table 2.1 (Neville, 1995).

Table 2.1 Components of Portland cement

Oxide	Symbol in Cement chemistry	Content
CaO	C	60-67
SiO_2	S	17-25
Al_2O_3	A	3-8
Fe_2O_3	F	0.5-6
MgO	M	0.1-4
Alkalis	N+K	0.2-1.3
SO_3	$\bar{S}$	1-3

The major oxides of Portland cement essentially include silica (SiO_2), lime (CaO), alumina (Al_2O_3) and iron oxide (Fe_2O_3). The major oxides of cement play a great role in the formation of the major compounds that determines both the fresh and hardened state properties of cement based materials. Furthermore, PC contains small amount of minor oxides as well which are magnesia (MgO), alkalis (Na_2O + K_2O) and sulphuric anhydride (SO_3). Minor oxides are often not contributing to the strength development of this binder. Therefore, their quantities are usually kept low as they cause great volumetric changes due to the complex expansive reactions and can result in cracking and disintegration of cement mortars. All the oxides in Portland cement are the oxides of clinker as well except SO_3. The clinker does not include SO_3. Sulphuric anhydride comes from the gypsum ($CaSO_4$ = $CaO.SO_3$) which used in the production cement along with clinker (Neville, 1995).

2.2.3.2 Major compounds of Portland cement

The major compounds that are obtained from heating of raw materials in the kiln are shown in Table 2.2 (Neville, 1995). These major compounds react with water independently during the hydration. Therefore, their concentrations play a great role in the determination of the final properties of these materials. For instance, C_2S and C_3S are the only compounds that are responsible from the strength development of cement based materials. Additionally, C_3S is the only compound responsible from the high early strength of cement based materials. C_3A and C_4AF do not contribute to the strength development and in fact, when they are present in large quantities, they can cause high heat liberation (due to hydration reaction) and fast rate of reaction that may cause thermal cracking and disintegration of cement-based materials.

Table 2.2 Major compounds of Portland cement

Name of Compound	Formula	Symbol in Cement chemistry
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium alumino-ferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

2.2.4 Hydration reaction of Portland cement

Hydration reaction is a chemical process that occurs when the cement and water mixed. The major components of the cement react with water, separately. Thus, the rate of hydration and the heat that is released by the reaction of each compound is different. Hence, each compound produces different products from the separated hydration reactions. The amount of hydration products in cement mortar directly affects the characteristics of cement mortar (Erdoğan, 2016). When Portland cement reacts with water, the production of portlandite crystal known as calcium hydroxide (CH) and amorphous calcium silicate hydrate gel (CSH) is formed. The main hydration reaction of Portland cement is given below (Neville, 1995):

$$\text{Cement} + \text{Water} \rightarrow \text{Calcium Silicate Hydrate} + \text{Calcium Hydroxide}$$

The hydration reactions of major compounds of Portland cement are shown below (Neville, 1995; Erdoğan, 2016):

Hydration of the calcium silicate compounds (C_2S and C_3S):

$$2C_3S + 6H \longrightarrow C_3S_2H_3 + 3CH$$

$$2C_2S + 4H \longrightarrow C_3S_2H_3 + CH$$

The products of the chemical reaction of both tricalcium silicate (C_3S) and dicalcium silicate (C_2S) with water are the same: CH and $C_3S_2H_3$. CH refers to calcium hydroxide ($CaO.H_2O=Ca(OH)_2$).

Hydration of C_3A:

$$C_3A + C\overline{S}H_2 + 10H \longrightarrow C_4A\overline{S}H_{12}$$

$$C_3A + 3C\overline{S}H_2 + 26H \longrightarrow C_6A\overline{S}_3H_{32}$$

The hydration of C_3A occurs very rapidly, and leads to the formation of calcium-alumino-hydrates. This rapid reaction of C_3A with water is very exothermic, and causes an immediate stiffening of cement paste which is known as quick set or flash set. In the case of quick set or flash set, the cement paste shows an immediate hardening and a significant strength development might not be observed. In order to observe the quick set, small amount (3%-6%) of gypsum is added to the clinker during the production of cement (Erdoğan, 2016).

Hydration of C_4AF:

The hydration of the major component C_4AF is similar to the hydration of the major component of C_3A. Here, aluminium oxides replaced with iron oxides. Although the rate and the heat of the chemical reaction between C_4AF and water is approximately as rapid and exothermic reaction as the chemical reaction between C_3A and water, C_4AF does not cause flash set as C_3A (Erdoğan, 2016). Water/binder ratio, particle size distribution, fineness and curing temperature are some of the factors affect the hydration of Portland cement (Neville, 1995). In the end of the hydration of Portland cement, 70% CSH, 20% CH and 10% minor compounds for example sulfo-aluminates are formed (Bapat, 2012).

2.2.5 The need for an alternative substitution material

In an environmental perspective, CO_2 can be considered as one of the major greenhouse gases (GHGs) which are primarily reason of the global climate change. Imbabi et al. (2013) stated that in every 1 kg of cement produced, approximately 0.9 kg CO_2 is formed as a by-product, which means 4.5 billion tonnes of carbon dioxide is formed from cement production only (Farfan et al., 2019). Moreover, it is expected to increment rapidly by the year 2050. The main sources of carbon dioxide in the production of cement are, (i) from the calcination, (ii) from the combustion of fuel which is used to heat the raw materials. An alternative substitution material can reduce the emission of CO_2 which comes from calcination.

2.3 Waste Materials

In light of trends in reduction of the greenhouse gas emissions to mitigate the climate change, partial substitution of Portland cement with waste materials has become common purposed practice. These waste materials are generally called supplementary cementitious materials (SCM). The details of the SCMs explained in detail in the following section.

2.3.1 Supplementary Cementitious Materials (SCMs)

Supplementary cementititous materials can be used in concrete or cement mortars. The use of SCMs such as silica fume or volcanic ash, leads to an important diminishment in CO_2 emissions as well as a solution to disposal of these wastes (Lothenbach et al., 2011). Supplementary cementitious materials can be classified in which two categories: self-cementing materials or pozzolanic. Self-cementing materials are the ones that give reaction in the same way with Portland cement; hardens during the irreversible hydraulic reaction just after merged with water. Coal fly ash and granulated blast furnace slag are primarily examples of self-cementing materials. Pozzolanic materials, generally have high amount of silica in composition, does not have cementitious properties when combined with water (Paris et al, 2016). Pozzolans can be further classified as either natural or artificial. Natural pozzolans remain unaltered from their unaltered state. Volcanic ash, diatomaceous earth, chert and shale can be given as examples for natural pozzolans. Artificial pozzolans include ground granulated blast furnace slag, rice husk ash, sugar cane bagasse ash, silica fume, recycled glass, biomass combustion ash, and coal fly ash (Paris et al, 2016).

2.3.2 Waste Materials in North Cyprus

In perspective of waste management, North Cyprus does not have advanced waste management technologies and/or regulations. Municipalities are responsible from collection, treatment and disposal of the wastes. In addition, Environmental Protection Department (EPD) is responsible for controlling the waste management systems for local municipalities (Özverel, 2014).

Table 2.3 Overall waste generations in North Cyprus

	Average generation, kg/capita/year	Per cent
Household waste	276.6	25.2
Commercial waste	127.8	11.6
Municipal waste	404.4	36.9
Construction/demolition	487.0	44.4
Green waste	56.2	5.1
Industrial waste	149.1	13.6
Total	1,096.8	100

The overall annually waste generation of North Cyprus is given in the Table 2.3 (EU Master Plan B, 2007).

2.4. Wood Waste

The use of biomass -which includes forestry and agriculture wastes- in the field of power generation as an alternative for fuel has incremented since the beginning of the research for renewable energy resources. This method is not only a cost effective way for power generation but also a highly efficient method for the disposal of wastes which produced while the manufacturing of forestry and timber products. Since the combustion of waste wood generates fewer fly ash and other residual substances with respect to the other biomasses i.e. agriculture wastes, wood wastes are more preferable for biomass furnaces (Ban and Ramli, 2011).

The incineration of aforementioned biomasses, when they are used in power generation as fuel, produces a significant quantity of ash as a by-product. Approximately 70% of these wood waste ashes are disposed in the way of land-filling which is a common method in all over the world (Etiegni and Campbell, 1991). However, wood waste ash has high amount of fine particles which can be can be easily transferred to the air by the wind and can cause important health problems such as respiratory troubles to occupants near the disposal area. Furthermore, underground water resources contamination can be occurred due to the leaching of heavy metals of ash (Udoeyo et al., 2006). Therefore, land-filling is uneconomical in long term and requires improvements in the sense of cost of disposal, due to the aforementioned reasons. Hence, a new method of disposal of wood waste ash is required to clarify these problems.

In addition, construction industry has raised in the world currently, which causes a significant increment in the indent for cement, the primary material in the manufacture of concrete (Ban and Ramli, 2011). The manufacturing of cement requires the use of the raw material, calcite (limestone), and high energy, while releasing extreme amount of carbon dioxide to the atmosphere at the same time. Numerically, 400 kg CO_2 gas is emitted for every 600 kg production of cement. The increment in the demand of concrete causes a higher rate environmental disruption since the extraction activities of limestone increments. Moreover, the enhanced demand of cement causes a superior requisite of fossil fuels which supply the required energy for the production cement, and this causes the higher emission of greenhouse gases (Ban and Ramli, 2011).

Udoeyo and Dashibil, (2002); Udoeyo et al., (2006) studied the potential of the wood waste ash as a fractional substitution material to cement in the manufacture of concrete in order to obtain energy efficient production. The tests demonstrate that the use of wood waste ash as a partial substitution material is reasonable and acceptable in terms of mechanical properties and durability characteristics of concrete. These determinations present a reasonable way out for the disposal of wood waste ash, contribute the waste management and provide opportunity for the production of greener concrete. Henceforth, the combination of wood waste ash as cement substitution material in cement based materials will be useful in environmental terms as well as in manufacturing prices of the aforementioned materials (Ban and Ramli, 2011).

2.4.1 Uses of wood waste ash

Wood waste ash should be recycled since the significant and expensive storage problems and environmental risks that unrecycled ash poses. Wood waste ash is used as a supplemental material to rise the alkalinity of soil in agriculture applications (Ban and Ramli, 2011). Moreover, wood waste ash is suitable for the construction discipline which can be used as a filler material for production of flexible pavements for roads or can be used as a supplementary material (Ban and Ramli, 2011).

2.4.2 Chemical composition and properties of wood waste ash

Wood waste ash is formed with the combustion of wood (Abdullahi, 2006). The major elements of the wood ash are Ca (calcium), K (potassium), Mg (magnesium), Si (silicon) and P (phosphorus) (Etiegni and Campbell, 1990). In addition to these elements, the major compounds in the wood ash are CaO, SiO_2, K_2O, MgO, Al_2O_3, P_2O_5,, Fe_2O_3, SO_3, Na_2O and TiO_2 (Vassilev et al., 2010).

The chemical structure of wood ash is significant because it affects its suitableness for the use as pozzolanic material in cement mortars and concrete. A pozzolan is an aluminous and siliceous material which has not cementitious properties but in the presence of moisture, reacts with calcium hydroxide - which comes from hydration of cement- to form compounds possessing cementitious properties (Ban and Ramli, 2011). According to this definition of ASTM, the existence of significant amounts of alumina and silica compounds in biomass fly ash is required in order to classify a material as pozzolanic.

X-Ray Fluorescence analysis made by Abdullahi (2006) and Elinwa and Ejeh (2004) showed that wood waste ash has a significant amount of silica in its chemical composition which comes from the uncontrolled incineration of wood waste. The total amount of pozzolanic essential compounds which are silica, alumina and ferric, has a mean value of 72.78% (Ban and Ramli, 2011). However, Naik et al. (2003) examined wood waste ash that received from five different resources, found that silica; alumina and ferric compounds have a range of 18.6 and 59.3%. Chemical reactivity of wood waste ash was found high with a pozzolanic activity index 76% approximately which is higher than the minimum 70% that stated by ASTM C618 (Ban and Ramli, 2011). According to the results of XRF analysis examined by Rajamma et al. (2009), wood waste ash samples which have higher amount of $SiO_2 + Al_2O_3 + Fe_2O_3$ composition have stronger pozzolanic activity than other samples which have lower amount of $SiO_2 + Al_2O_3 + Fe_2O_3$ content.

2.5 Properties of wood waste ash blended cement

2.5.1 Soundness

Soundness of the cement mortar or concrete is the measure of robustness which refers to a volume expansion after setting of cement mortar in the presence of free lime (CaO) and magnesium oxide (MgO). The excess amount of CaO and MgO in cement causes a volume expansion after setting. The hydration of these materials occurs very slowly since the high amount of temperature during their formation in the rotary kiln. Thus, the reaction of the free lime and magnesium oxide with water takes months after hardening of cement mortar or concrete. This hydration of CaO and MgO causes' expansion of hardened concrete, therefore, cracks can be formed in the hardened concrete. The soundness of cement is measured in mm and the upper limit for the soundness of cement to be sound is 10 mm which is specified by BS 4550-Part 3 (Erdoğan, 2016; Udoeyo and Dashibil, 2002).

The results of soundness tests on blended cement with the presence of wood waste ash as a partial cement substitution are higher than that of control cement. This means the presence of wood waste ash in blended cement paste increment the soundness, in other words reduction the expansion of cement (Rao, 2003). Elinwa and Ejeh (2004), Udoeyo and Dashibil (2002) and Elinwa and Mahmood (2002) studied that using wood waste ash as a partial cement substitution with 30% substitution level, the most sound blended cement was observed which was approximately 1.50 mm that is under the upper limit of 10 mm specified by BS 4550-Part 3.

2.6 Mechanical properties of cement based materials

2.6.1 Strength

Neville (1995) stated that strength is considered as the most important property to discuss the quality of concrete and cement mortars. Strength gives a general view about the quality of hydrated cementitious paste. Strength can be related with quality of concrete and cement mortars since the sum of volume of the gel pores and capillary pores existing in cementitious paste is indirectly proportional to the volume of hydrated cementitious paste. In other words, the strength development of hydrated cementitious paste is high in the case where the volume of gel and capillary pores is low. Strength is measured in MPa or pounds per square inch (psi) (Neville, 1995; Kosmatka, 2011).

Strength of concrete is assumed to depend mainly on two factors: water/cement ratio and the degree of compaction. If the concrete is fully compacted, the water/cement ratio is inversely proportional to the strength of concrete. The higher the water/cement ratio, the higher the air voids on the surface of concrete and thus, the lower the strength. High water/cement ratio will damage the bonds between the cementitious paste and filler particles such as coarse aggregates, which causes segregation in hardened concrete. The optimum water/cement ratio provides enough workability, since lower than optimum water/cement ratio will make the concrete compaction hard, thus the strength will be affect (Neville, 1995; Erdoğan, 2016).

Aggregates used in the production of concrete should contain trace amount of reactive silica and reactive carbonate. Reactive silica and carbonate react with alkaline in cement and cause alkaline-aggregate gels. These alkaline-aggregate gels have large expansion capacity and cause cracks and fractures in hardened concrete. The fractures in the hardened concrete originated from the weak bonds between coarse aggregates and cement paste. The bond between coarse aggregates and cement paste is formed from van der Waals forces and the adherence between coarse aggregates and cement paste. Hence, the strength of concrete arises from water/cement ratio, degree of compaction, strength of coarse aggregates, strength of cementitious paste and the bond between the coarse aggregates and cement paste (Erdoğan, 2016; Nevile, 1995; Kosmatka, 2011).

2.7 Durability characteristics of cement mortar

2.7.1 Porosity

Porosity of cement mortars can be defined as the ratio of volume of pores to the total volume of cement mortar. Porosity of cement mortars depends on the amount of pores of structure of cement mortars. Porosity is a qualitative property. It can be obtained by determining the absorption capacity of cement mortar. In case of 'porous' cement mortar, water or other fluids can transport through it, and cause reduction in the strength of cement mortar (Neville, 1995; Erdoğan, 2016).

2.7.2 Water Permeability

Permeability is a property of cement mortar that allows fluids to transport through it. Water, carbon dioxide and oxygen can be given as examples of fluids. Transportation of the fluids mainly depends on continuousness of the pores in cement mortar and the structure of hydrated cement paste.

Water permeability of cement mortars is the flow of water through cement mortar, which is caused by the porous structure of mortar. Permeability of cement mortar is related with the capillary pores exist in the hydrated cement paste of cement mortar. It should be noted that water permeability and porosity are different properties of cement mortars. Water permeability depends on the magnitude, distribution, form and steadiness of pores inside the pore system of hydrated cement paste of cement mortars (Neville, 1995; Erdoğan, 2016; Kosmatka, 2011).

2.7.3 Freeze and Thaw

Freeze and thaw is a physical process of concrete and cement mortars. Pure water freezes at 0ºC, however, water inside the cement mortar freezes at a lower temperature because of the impurities such as molten salts inside the cement mortar. Moreover, the size of the pores inside the cement mortar affects the freezing point of water. For instance, the water inside larger capillary pores has higher freezing point whereas inside smaller capillary pores have lower.

When liquid water freezes, volume expansion occurs. The iced water applies a hydraulic pressure on the unfrozen water in the capillary pores because of the volume expansion of ice. This hydraulic pressure results in transportation of the unfrozen water to surface of the cement mortar through the capillary pores. The unfrozen water which is forced to move through the capillary pores causes tensile stresses that can create failures and cracks in the cement mortars.

The iced water melts and the tensile stresses in cement mortar vanish when temperature of the cement mortar increments. However, the same cases can be experienced at any time when the temperature reductions. All the concrete and cement mortars get damaged if they are exposed to continuous freeze and thaw cycle (Neville, 1995; Erdoğan, 2016).

2.8 Discussion

It is clear from the literature survey that the manufacture of cement is not an environmentally friendly process and hence, 1 tons of CO_2 is released to the atmosphere during the production of 1 tons of cement. Waste generation and existing waste management options particularly in the developing countries are becoming more and more dramatic each year. For instance, the waste wood generated in the industrial sector of North Cyprus is not being managed in anyway. The existing methods such as landfilling and incineration could also bring more complications such as soil contamination or carbon dioxide emissions. Taking these concerns into account, the thesis is focusing on the use of waste wood, in the form of wood powder and wood fibre, as a substitution material in cement mortars. Chemical, physical, mechanical properties as well as cost effectiveness are studied in this thesis.

CHAPTER III

MATERIALS USED

3.1 Cement

Portland cement was used as a binder material for production of the concrete. Adana Cimento Ltd. is the manufacturer of Portland cement which was used for this thesis. Portland cement has a specific gravity of 3.15 and has design strength of 32.5 MPa. Particle size distribution and X-ray florescence (XRF) were conducted to determine the chemical composition of Portland cement at Central Laboratory, METU Ankara.

3.1.1 Particle size distribution of cement

Particle size distribution of Portland cement is given in Figure 3.1.

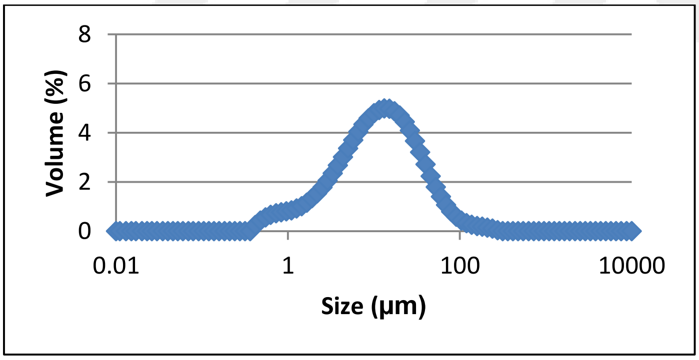


Figure 3.1: Particle size distribution of Portland cement

3.1.2 Chemical composition

Chemical composition of Portland cement is given in Table 3.1.

Table 3.1: Chemical composition of Portland cement

Component	wt%
CaO	43,8
SiO_2	30,2
Al_2O_3	11,4
Fe_2O_3	5,11
SO_3	3,29
MgO	2,61
K_2O	1,34
TiO_2	0,738
Na_2O	0,51
MnO	0,429
SrO	0,187
P_2O_5	0,165
BaO	0,132
Cl	0,0383
NiO	0,0223
ZnO	0,0142
CuO	0,0079

3.2 Sand

Standard sand was used as a filler material for the production of cement. Standard sand was manufactured by Limak Batı Cimento San. ve Tic. As. and it is in compliance with TS EN 196-1.

3.2.1 Particle Size Distribution

Particle size distribution of sand is given Figure 3.2.

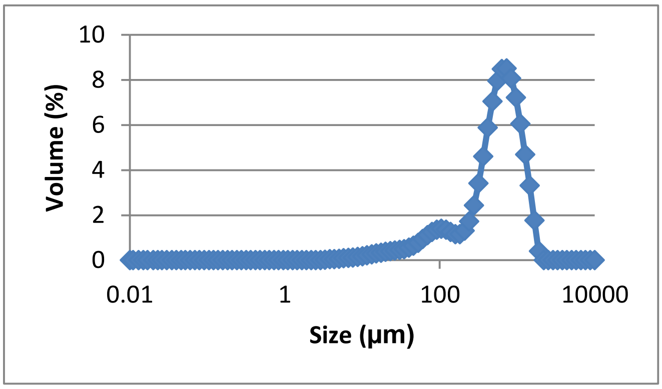


Figure 3.2: Particle size distribution of sand.

3.2.2 Chemical Composition

Chemical composition of sand is given in Table 3.2.

Table 3.2: Chemical composition of sand

Component	wt%
SiO_2	91,9
Al_2O_3	3,91
K_2O	1,31
TiO_2	0,832
Fe_2O_3	0,659
Na_2O	0,498
CaO	0,463
MgO	0,142
BaO	0,0831
P_2O_5	0,0597
SO_3	0,0411
MnO	0,0398

Table 3.2 (continued)

Cr_2O_3	0,0241
Cl	0,0178
SrO	0,0152
ZrO_2	0,0143
Rb_2O	0,0071

3.3 Waste Materials

Wood fibre and wood powder were used as a partial substitution material for both cement and sand in the production of cement mortars. Both wood fibre and wood powder were received from qualified industrial zone of Güzelyurt.

3.3.1 Wood Powder

Wood powder is used as a partial substitution for both sand and cement in cement mortars. It was received from a carpenter from qualified industrial zone in Güzelyurt. Figure 3.3 shows the particle size distribution of wood powder.

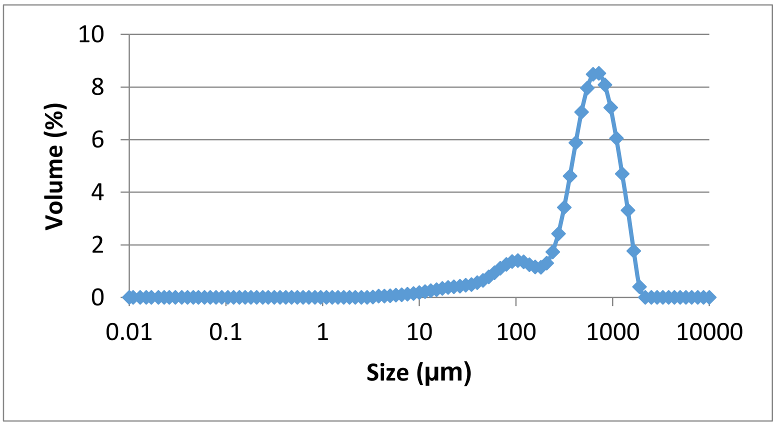


Figure 3.3: Particle size distribution of wood powder

3.3.2 Chemical Composition

Chemical composition of wood powder is given in Table 3.3.

Table 3.3: Chemical composition of wood powder

Component	**wt%**
ZnO	43,2
CaO	20,1
SiO_2	19,2
K_2O	4,49
Fe_2O_3	3,26
MnO	2,63
Cl	2,01
SO_3	1,83
Al_2O_3	1,59
MgO	1,35
P_2O_5	0,282

3.3.3 Wood Fibre

Wood fibre is used as a partial substitution material for both cement and sand in the production of cement mortars. Wood fibre was also received from a carpenter from qualified industrial zone in Güzelyurt. The nature of wood fibre is not suitable for determining identifying its chemical and physical properties as well as particle size distribution. Figure 3.4 is a picture of wood powder (left) and wood fibre (right), respectively.

Figure 3.4: Wood powder (left) and wood fibre (right)

3.4 Water

The amount as well as quality of water in cement mortars is important since water has a direct effect on the strength of concrete and cement mortars. In this thesis, quality and quantity of water used for cement mortars and curing, is in compliance with ASTM C94 and ASTM C1602.

CHAPTER IV

METHODOLOGY AND EXPERIMENTAL PROCEDURE

4.1 Methodology

The thesis is addressing the effects of the inclusion of wood powder and wood fibre in cement based materials. The use of waste wood products was specifically chosen to help the sustainable development of concrete. The research methodologies for this thesis is conducted both at Materials Laboratory of METU NCC as well as partly conducted at the Central Laboratory of METU Ankara campus. Mechanical experimentation and durability study mainly are facilitated at Materials Laboratory of METU NCC and advanced techniques such as X-ray florescence were performed at Central Laboratory of METU Ankara campus. The research methodology conducted for the thesis are detailed herein.

4.2 Characterisation of raw materials

Characterisation of raw materials are obtained using the measurement techniques below:

4.2.1 X-ray fluorescence

To obtain the elemental composition of the raw waste materials to determine its suitability in cement matrix.

X-Ray fluorescence (XRF) spectrometry is used in order to identify the elemental compositions of the raw materials. The wavelength of radiation of the testing element is different and distinctive for each element. Type of the element can be identified by detecting the wavelength of radiation, concentration of the element is measured by determining the concentration of the radiation. From Boron (B) through Uranium (U), it is possible to make quantitative analysis by X-Ray fluorescence spectrometry. The elemental compositions of samples were determined by XRF at Central Laboratory of METU Ankara.

4.2.2 Particle size distribution

To determine the particle size of the waste materials and to compare this with the particle size of cement and sand.

Durability, chemical reactivity, opacity, fluidity and strength of materials depend on particle size characteristics of the materials. For this thesis, Malvern Mastersizer 2000 is used to determine the particle size distribution of the materials within the range of 0.02 and 2000 μm. ASTM D4464-15 (2015) is followed to verify the particle size distribution of the materials. Particle size distribution of the samples is carried out at Central Laboratory at Ankara.

4.3 Mechanical Properties

Mechanical properties measured in this thesis are the compressive and flexural strength. Experimental procedures of those are given herein.

4.3.1 Compressive strength

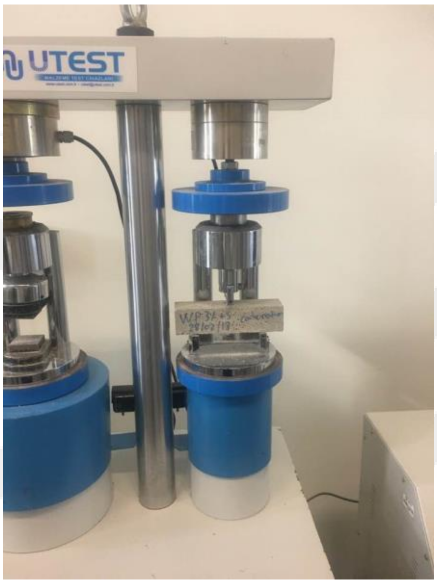
Strength is one of the most important parameter to determine the mechanical properties of cement based materials. Compressive strength will be conducted at 7^{th}, 14^{th} and 28^{th} days to the development of strength.

Figure 4.1: Compressive and flexural strength test machines

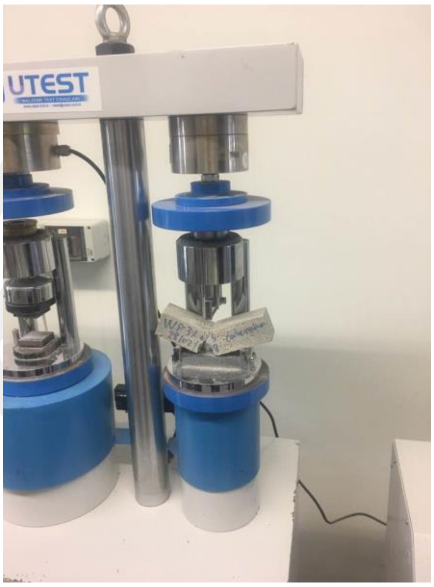
Compressive strength of cement mortars is measured in order to determine the upper limit of compression on the cement mortars. In order to measure the compressive strength, experiment is conducted according to ASTM C109/C109M (2016). Before the experiment, the samples are cured at specific curing days and then air-dried. The machine includes two flat plates where the load is equally distributed and has a loading rate of 2.4 kN per second. The specimens are positioned in between these plates and load is applied until the failure of samples is occurred. The compressive (left) and flexural (right) strength test machines are shown in Figure 4.1.

4.3.2 Flexural strength

Flexural strength will be conducted at 7th, 14th and 28th days to the development of strength. Flexural strength test allows to measure flexural strength of hydraulic cement mortars. ASTM C348- 18 (2018) is followed while conducting the experiment. The flexural strength testing device has 15kN capacity and applies load to the mortar prisms by centre point loading method. The applied load is vertical to the specimen. The device has two flat plates and the upper plate has a metal rod at the centre. First, the specimen is placed between the two flat plates. The metal rod of upper plate was on the centre of the specimen. The flexural strength test machine applies the load until the specimen is broken into two parts. Then the two parts of the specimen is used in compressive strength test separately. Figures 4.1 (a) and (b) show the sample in the flexural strength testing machine before and after the break, respectively.



(a) The sample before the break



(b) The sample after the break

Figure 4.2: Flexural strength test machine

4.4 Physical Properties

Physical properties measured in this thesis are sorptivity, porosity, water penetration depth.

4.4.1 Water Penetration Test

Water penetration depth test is conducted in order to determine the water permeability level of concrete and cement mortars. The standard BS EN 12390-8 (2009) is followed to perform the experiment. Firstly, dry mass of samples, which is recorded as initial mass, is measured prior to the experiment. Secondly, the samples are placed into the water permeability testing machine. The placement should be done carefully in order to avoid any water leakage from the samples. Then, pressurized water is applied from the bottom of the samples for 72 hours. After 72 hours, all the samples are removed from the water permeability testing machine and the final masses of the samples are measured. Then split tensile test is performed in order to divide the samples into two. After few minutes resting of the sample, the water level is marked by a broad marker. The distance between the bottom of the sample and marked line is measured by a ruler. Mass of absorbed water is calculated by subtracting initial mass from final mass of the sample. The picture of the water permeability testing machine is shown in Figure 4.3.

Figure 4.3: Water permeability testing machine

4.4.2 Sorptivity

Sorptivity is the measure of liquid absorption capacity. It is very important to measure this parameter to find out the influence of the wood waste on water absorption capacity of cement mortars.

ASTM C1585-13 (2013) is followed in order to perform the sorptivity test. Samples are soaked in a shallow layer of water in a tray for 1, 4, 9, 16 and 25 minutes. To enable unidirectional absorption of cement mortars, samples are placed on small wedges. They are taken out of water at specified times and then placed on a top loading balance for mass measurements. Cumulative volume of water per unit area of samples are then plotted with respect to the time to the half. The slope of this curve provided the sorptivity in mm/min$^{1/2}$.

4.4.3 Porosity

This parameter measures the pores in cement mortars which directly affects the compressive strength.

Determination of porosity is conducted by mercury porosimetry. ASTM D4404-10 (2010) is followed while carrying out the experiment. The working of mercury porosimetry based on a principle that an inert liquid cannot penetrate into small pores, if the pressure on the liquid is not sufficient. Mercury cannot penetrate into the pores of the cementititous samples when required pressure does not exist. More pressure is required for smaller pores; less pressure is required for larger pores since the pressure is inversely proportional to the diameter of the pores of the specimen. The volume and size distributions of the pores of samples can be determined by the data of applied pressure versus mercury intrusion. Determination of porosity was conducted at Central Laboratory at Ankara.

4.5. Durability characteristic

Durability is the ability of a concrete material to resist the external effects to expand the service life. The experimentations to define durability are freeze and thaw resistance of concrete for this study.

4.5.1 Freeze and thaw resistance

This action of temperature change usually takes place at the hardened concrete. When the pores are saturated, freezing cause the volume expansion and this is received as a hydraulic pressure by concrete specimen that causes cracking and loss of strength. There is a freeze and thaw cabinet at Materials Laboratory of METU NCC that can make 2 cycles of freeze and thaw a day which operates in -30° and +30° to simulate the freeze and thaw action. Samples are cured in this cabinet for their lifetime and are then subjected to a compressive strength test to find the loss of strength in percent.

Resistance to freeze and thaw is measured in order to determine the behaviour of the cementitious mortars when exposed to sharp temperature changes. ASTM C666/C666M-15 (2015) is followed to conduct experiments. The experiments comprise a temperature change cycle in a closed chamber for a specified period of time. The temperature cycle is between -30°C and +30°C. Standard 40x40x160 mm beam samples are used for freeze and thaw testing. The samples are water cured for 28 days prior to they were subjected to the chamber. The initial masses of the samples are measured prior to the placement into the chamber. The temperature change cycle is occurred twice in a day in the closed freeze and thaw chamber for one year. After the samples are taken out from the chamber, final mass of the specimens is measured. Resistance to freeze and thaw of the specimens is measured by calculating mass loss of the samples by subtracting the final mass from initial mass of the samples. Determination of the resistance to freeze and thaw is also conducted by comparing the compressive strength of the samples with compressive strength of control sample which is water cured only. The freeze and thaw closed chamber is shown in Figure 4.4.

Figure 4.4: Freeze and thaw chamber

4.6 Mix Design Principles

Cement mortars designed for this thesis are obtained using the fixed mix proportion (0.78:1:2 mix water: binder: sand) by volume. Standard and sieved single source sharp sand is used in the experimental part of this thesis. Bulk density of mortars are first measured. Simply the volume of the given raw material is measured using the volumetric flask and mass of this sample is taken using the top loading balance. Volume proportions are determined to be 0.78:1:2 which is the binder: water: sand ratio. Mass of the required raw materials for cement mortar making is then calculated simply by multiplying the volume proportions with bulk density of the materials (Ince, C., 2015 and Ince et al., 2015).

Waste wood in the form of wood powder and wood fibre used in this thesis is combined in cement mortars both as a binder substitution and sand substitution. When these waste materials are used as a cement substitution material, then the volume proportion of cement is reduced and the same proportion of the waste wood is then combined in mortars. In the case of a sand substitution, the volume proportions of sand are then reduced and the same amount of volume proportions of sand is then added to the mix.

4.7 Mixing procedure

The standard mixing procedure was used for making cement mortars in this thesis. Water was placed into the mixing bowl first and the cement is then added. Mixing cement and water first are important for the hydration reaction. These are mixed for 1 min. Without interrupting the mixer, sand was then added gradually over the following 1 min. Mortars were then mixed for one more minute. The mixer was then stopped. Spatula is used to mix the solids scraped from the paddle and the sides of the mixing bowl. Total mixing time was remained to be 10 minutes for all the mixes examined in this thesis.

4.8 Consistency

Consistency measurement was conducted with flow table device to measure the consistency of cement mortars. Flow table consists of a rigid iron mould, rigid table top and a handle vertically attached to the device. Experimental procedure was conducted with respect to ASTM C230 (2014). Before starting the experiment, the iron mould is oiled. Then, cement mortar is filled and smoothed in the mould. After, the mould is removed. The handle is subsequently rotated by hand with the speed of 1 revolution per second for 15 times. This action presents a vertical movement of table top with a height of 12.5 mm allows the cement mortar to spread on the table top. The optimum consistency should vary between 130 mm and 140 mm in order to achieve the optimum workability.

CHAPTER V

EXPERIMENTAL RESULTS

5.1 Introduction

This chapter reports the experimental results of cement mortars combined with wood powders and wood fibres. Chapter is mainly divided in 6 main categories. Mix design principles are given in the beginning of the chapter. Characterization study conducted by the particle size analysis and X-ray fluorescence are then reported. Fresh state properties of cement mortars are also reported in this chapter. Mechanical properties such as compressive and flexural strength of cement mortars combined with waste wood are noted in Section 5.5. Water penetration depth, sorptivity and porosity of cement mortar combining waste wood are also addressed in Section 5.5. Durability characteristics such as resistance to freezing and thawing, and resistance to carbonation of cement mortars with waste wood are discussed at Section 5.6. Lastly, cost efficiency of cement mortars combining wood powders used both as sand and cement substitution materials is examined in Section 5.7.

5.2 Mix Design

The principles of mix design calculations of cement mortars are noted and emphasized once again that wood waste materials (both wood powder and wood fibre) are used as a substitution to both cement and sand in cement mortars. In order to incorporate a particular type of wood waste as a substitution to a raw material in cement mortars, a specified amount of volume proportion of the raw material is reduced and hence the same volume proportion of the substitution material is then added to the mixture. Mix design of cement mortars as a reference or a control specimen in this thesis is given in Table 5.1.

Table 5.1: Representative example of mix design calculations for 1% wood powder used as sand substitution in cement mortars

WPS (1%)	Materials	Density (g/cm^3)	Volume Proportion	Mass (g)	Total Mass (g)
	Water	1	0,48	0,48	456
	Cement	1,14	0,99	11,286	1072,17
	Wood Powder	0,237	0,01	0,0237	22,515
	Sand	1,59	1,4	2,226	2114,7

Table 5.1, summarizes the mix design calculations of cement mortar combined with 1% wood powder. Bulk density values of the raw materials are reported as g/cm^3 first. Then volume proportions of 0, 48: 1: 1, 4 was adopted for water: binder: sand ratio. In this case wood powder is used as a cement substitution in cement mortars and hence volume proportion of cement mortar is reduced to 0, 99 and 0, 01 which is 1% wood powder is introduced into the mix. It must be noted that volume proportions of cement and wood powder (0, 99 to 0, 01) still add up to 1. The mass of these ingredients were solely evaluated by multiplying the density and volume ratios. As it can be seen in Table 5.1, these mass fractions are very small therefore a constant volume (950) is used to multiply the mass fractions of these ingredients so that minimum of 6 beams of 40x40x160 mm could be obtained from each cast work.

5.3 Characterisation of raw materials

Characterisation of raw materials are achieved using particle size distribution and X-ray fluorescence in this thesis. Particle size distribution provided information about the fineness of the wood powder employed both as a sand and cement substitution material in this study.

X-Ray fluorescence was adopted for the determination of the chemical structure of the raw materials.

5.3.1 Particle Size Distribution

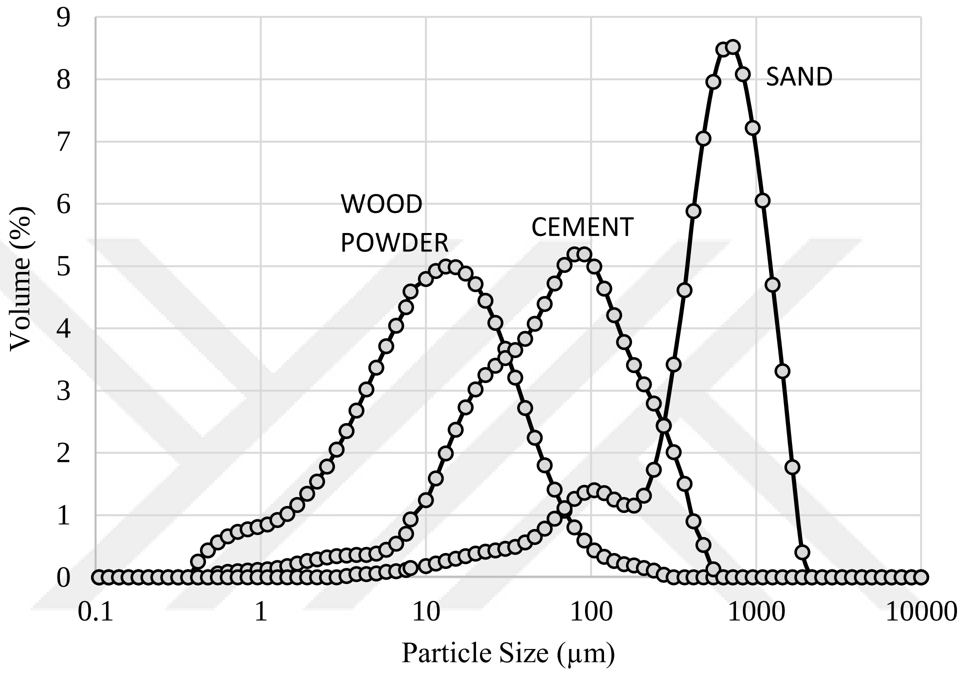


Figure 5.1: Particle size distribution of raw materials

Particle size distribution of raw materials namely wood powder, cement and sand are shown in Figure 5.1. As it was anticipated, wood powders have much higher fineness when compared to cement and sand. Particle size distribution of wood powders are ranging from ~0,6 µm to ~ 200 µm whereas cement is in the range of ~ 8 µm to ~ 800 µm and sand is in the range of ~ 9 µm to ~ 4 mm.

It must be emphasized that wood powders employed both as cement and sand substitution materials in cement mortars have higher fineness and therefore they have an incremented surface area and can act as 'filler' material in the mixture.

5.3.2 X- Ray Fluorescence

X-Ray fluorescence, used to study the chemical compositions of the raw materials is summarised in Table 5.2. As expected, cement is rich in CaO and SiO_2 content. The rest of the distribution of its content is a typical composition of cement binder. Fine aggregate (sand) also has a very typical composition. It is very rich in SiO_2 which is about 91%. Al_2O_3, K_2O and TiO_2 are also present in its compositions as an impurity. When the composition of wood powders is studied, it can be seen that they have a high content of ZnO, CaO and SiO_2. K_2O, Fe_2O_3 and MnO may be present as a minority.

Since wood powders do not contain minimum of 70% of SiO_2, Al_2O_3 and Fe_2O_3 in its composition, it was concluded that they would not possess any pozzolanic activity when combined in cement mortars. They also don't have any cementitious value. It must therefore be noted that wood powder and wood fibres used in this study are chemically inert materials.

Table 5.2: Chemical analysis of the raw materials

Cement		Wood		Sand	
Component	wt%	Component	wt%	Component	wt%
CaO	43,8	ZnO	43,2	SiO_2	91,9
SiO_2	30,2	CaO	20,1	Al_2O_3	3,91
Al_2O_3	11,4	SiO_2	19,2	K_2O	1,31
Fe_2O_3	5,11	K_2O	4,49	TiO_2	0,832
SO_3	3,29	Fe_2O_3	3,26	Fe_2O_3	0,659
MgO	2,61	MnO	2,63	Na_2O	0,498
K_2O	1,34	Cl	2,01	CaO	0,463
TiO_2	0,738	SO_3	1,83	MgO	0,142
Na_2O	0,51	Al_2O_3	1,59	BaO	0,0831
MnO	0,429	MgO	1,35	P_2O_5	0,0597
SrO	0,187	P_2O_5	0,282	SO_3	0,0411
P_2O_5	0,165			MnO	0,0398
BaO	0,132			Cr_2O_3	0,0241
Cl	0,0383			Cl	0,0178
NiO	0,0223			SrO	0,0152
ZnO	0,0142			ZrO_2	0,0143
CuO	0,0079			Rb_2O	0,0071

Table 5.2 shows the results of XRF analysis of cement, wood powder and sand. In terms of elements and oxide components they involve, wood powders have similarities with sand

according to these results. This can be the reason of better mechanical properties of cement mortars combined with wood powder as sand substitution.

5.4 Fresh Properties and Observations

Consistency and setting time measurements were conducted to address the fresh properties of cement mortar combined wood powders and wood fibre in this study. The influence of saturating the wood powders and wood fibres were also discussed in this section of the thesis.

5.4.1 Consistency

Consistency of cement mortars combining wood powders both as sand and cement substitutions are shown in Figure 5.2. Consistency of cement mortars used as a reference specimen was 125 mm. It is shown in Figure 5.2 that increment in the substitution levels of wood powders employed both as sand and cement substitutions caused a minor reduction in consistency of cement mortars.

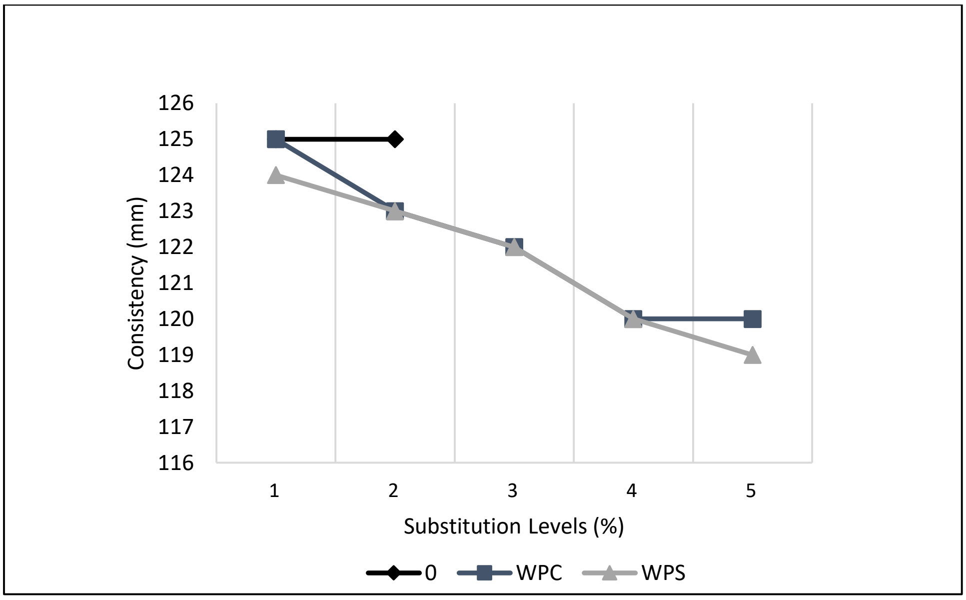


Figure 5.2: Consistency of cement mortars combining wood powders

The greater reduction in consistency of cement mortars when wood powders were used as sand substitution were observed. Reduction in consistency of cement mortars combining wood powders could be attributed to the increment fineness and therefore increment surface area of the fine materials at the freshly mix stage. Increment surface area results in a higher water demand to achieve the same consistency however it must be noted that the water content of the mix was not incremented in the study deliberately first; in order not to change the w/c ratio of all the cement mortars examined in the thesis (as change in w/c ratio dramatically changes the mechanical properties as well as durability) second; the reduction observed in consistency was found to be very small and that the mixture was still 'workable' with the slight reduction in consistency. It should not be forgotten that substitution levels of wood powders used in this study go up to 5% and therefore the fineness introduced into the mixture could be tolerated. Author suggests that plasticisers could be used to achieve standard consistency of higher volume fractions of wood powders were employed.

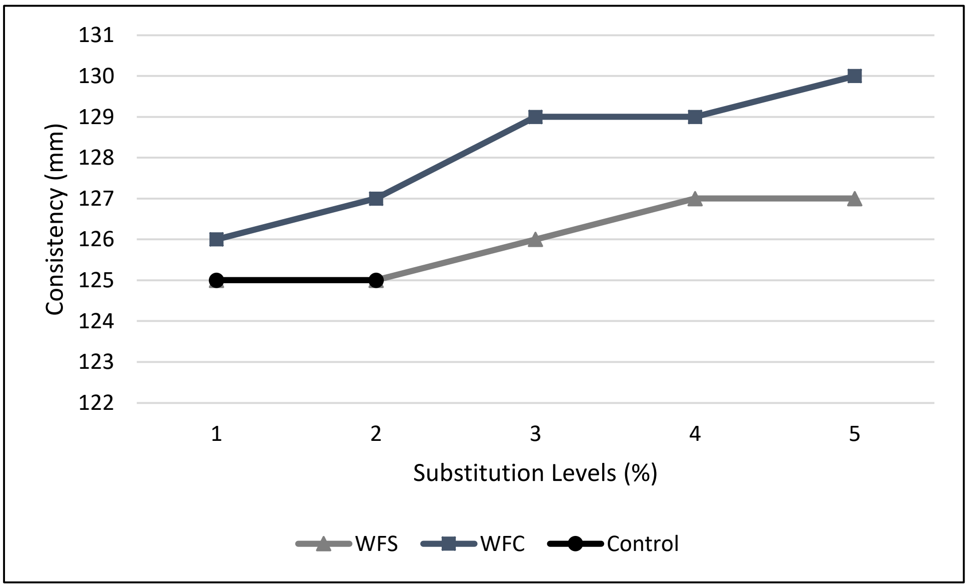


Figure 5.3: Consistency of cement mortar combining wood fibres

Consistency of cement mortars combining wood fibres are shown in Figure 5.3. It must be noted that once again that consistency of cement mortars used as a reference specimen in this section was found to be 125 mm. It is shown in Figure 5.3 that increment in the substitution level of wood fibres used both as cement and sand substitutes caused an increment in consistency of cement mortars. This was anticipated as courser particle size of wood fibres are used to replace cement and sand in cement mortars. Greater increment in consistency of cement mortar combining wood fibre as cement substitutions could be attributed to the greater difference in the particle size distribution of cement and wood fibres.

5.4.2 Setting Time

Setting time of cement mortars combining wood powders both as cement and sand substitutes are shown in Figure 5.4. Setting time of cement mortars, used as a reference specimen in this study, was also plotted in Figure 5.4 for comparison.

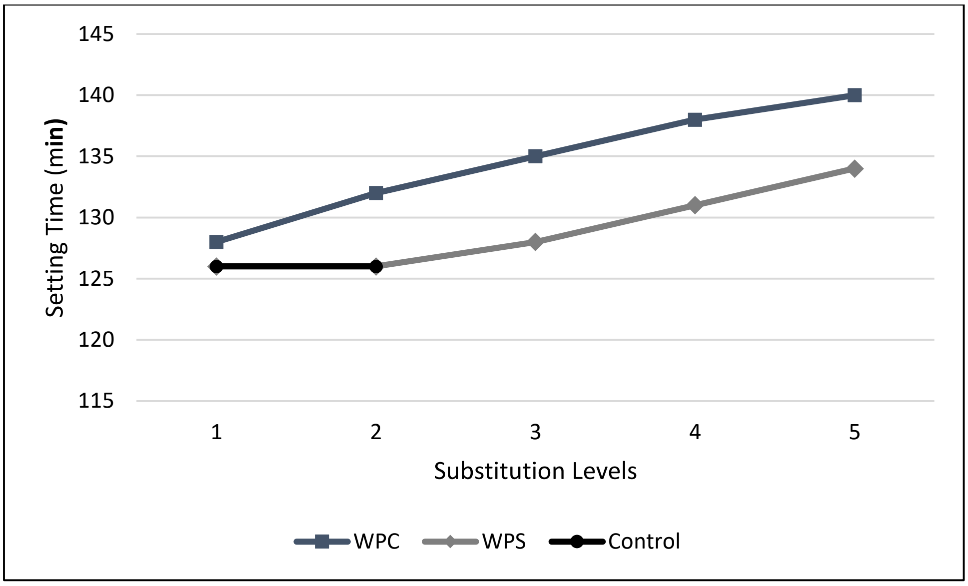


Figure 5.4: Setting time of cement mortars combining wood powders

It is shown in Figure 5.4 that growth in the substitution levels of wood powders used both as sand and cement substitutions caused an increment in setting time of cement mortars. However, it should not be forgotten that greater increment in the setting time of cement mortars when wood powders are combined as cement substitution were observed. In this case, hydraulic binder cement was partially replaced by an inert material, wood powder. So there is less cement available in the mixture to react with water. Wood powders are completely inert and therefore they do not contribute in the stiffening process or in the chemical reaction with water within the mix. It is anticipated that when wood powders are used as cement substitution, a reduction in the amount of cement would result in a delayed reaction and hence would delay the setting time of cement mortars. The increment in setting time of cement mortars combining wood powders as sand substitutions could be attributed to the weaker interface and therefore weaker mechanical anchorage properties of wood powders compared to sand and cement.

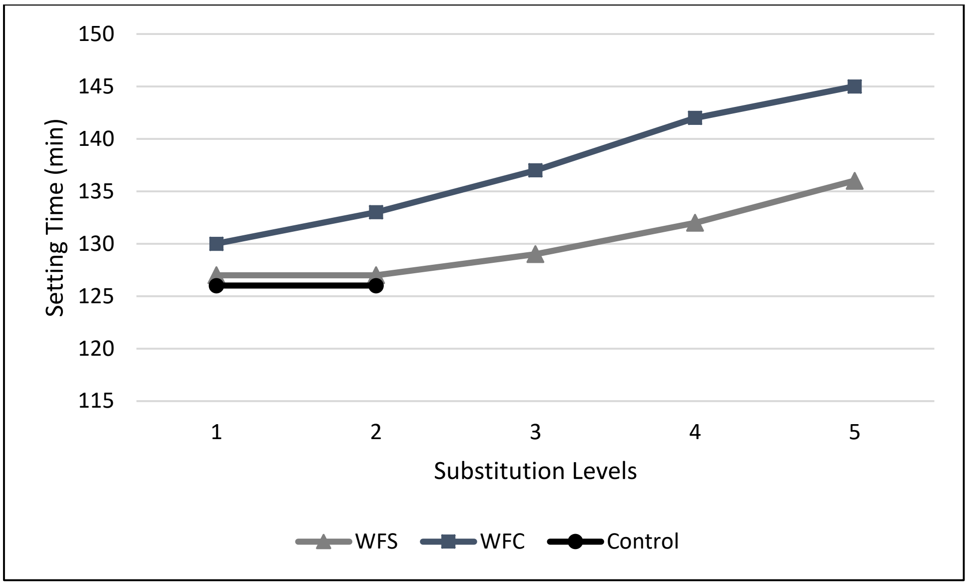


Figure 5.5: Setting time of cement mortars combining wood fibres

Setting time of cement mortars combining wood fibres both as cement and sand substitutions are shown in Figure 5.5. Figure 5.5 shows that increment in the substitution levels of wood fibres resulted in an increment in the setting time of cement mortars. This observation is attributed to the increment particle size of raw materials within the mix that causes bigger air voids to take place in the matrix as well as the weaker mechanical bonding that wood fibres have within the mixture compared to cement and sand. These changes result in a delayed hydration reaction which could possibly results in a delayed setting.

5.4.3 Saturation Process

It is previously discussed in Section 5.4.1 'consistency' that rise in the substitution levels of wood powders results in a decline in consistency of cement mortars. It was also noted that this observation is attained as a result of the incremented fineness of the mixture that also resulted in an incremented water demand to attain same consistency as the reference mixture.

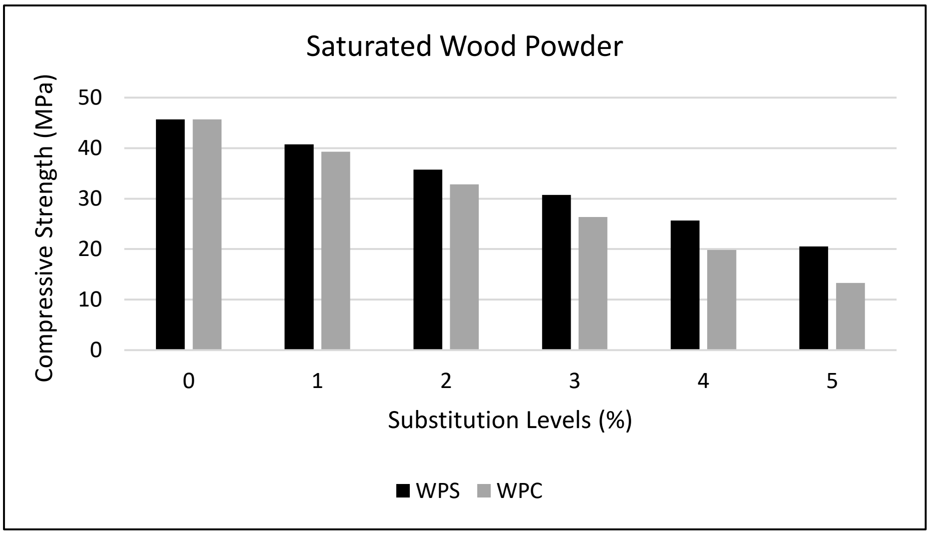


Figure 5.6: Compressive strength of cement mortars combining wood powders

It was therefore decided to conduct a pilot study to investigate the influence of saturating wood powders on the consistency as well as on the hardened state properties of cement mortars. Wood powders were first soaked in water for 24 hours. Following they were removed from water, their surface was dried using a hair-dryer. This procedure is well-known for fine aggregates to obtain ‘saturated surface dry’ (SSD) moisture state. It was thought that if the wood powders could be turned into saturated surface dry state, they would not absorb water from the mixture as they are fully saturated inside, they would also not deliver excess water into the mixture as they have dry surfaces.

This was found to be an effective method to achieve higher consistency in cement mortars however it was not at all found to be appropriate to be used when hardened state properties were measured. It was observed that, wood powders were actually absorbing quite a lot of water when they were soaked in water for 24 hours and that following they were combined into the mixture, they caused a dramatic increment in overall water cement ratio which adversely affects the mechanical properties and durability characteristics of cement mortars.

The main reason for such an increment in water absorption of wood powders is explained here in. When the wood powders are soaked in water, there is a multi-directional water absorption available. However, when wood powders are combined in cement mortars, free water which could be absorbed by the wood powders were very limited. Water in the cement mortar first of all covers the surface of the cement particles that go into a chemical reaction and then covers the surface of all fine aggregates. So under this configuration, free water available for the wood powders to absorb is much less.

5.5 Mechanical Properties

This section addresses the mechanical properties of cement mortars combining wood powders and wood fibres used as both sand and cement substitution materials. Mechanical properties of cement mortars are examined by conducting compressive strength and flexural strength tests. Influence of wood powders and wood fibres as well as their increasing substitution levels on the compressive and flexural strength of cement mortars are examined in this section.

5.5.1 Compressive Strength

Compressive strength of cement mortars with increasing substitution levels of wood powders and wood fibres are reported in this section.

5.5.1.1 Compressive strength of cement mortars combined wood powder

Compressive strength of cement mortars combining wood powders both as cement and sand substitutions is investigated in this section. Figure 5.7 shows the compressive strength of cement mortars with increasing substitution levels of wood powder.

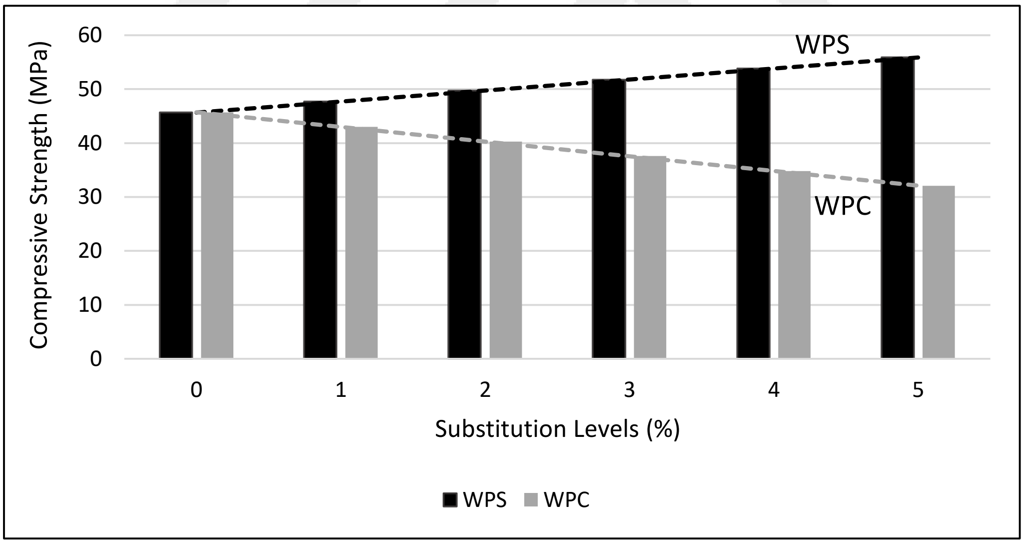


Figure 5.7: Compressive strength of cement mortars combined wood powders used as, ■; sand substitute, ■; cement substitute.

Figure 5.7 shows that rise of substitution degree of wood powders employed as cement substitution caused a systematic decrement in the compressive strength of cement mortars. This must be attributed to the inert character of wood powder that does not contribute in the hydration reaction of cement and therefore does not positively influence the strength gain of the matrix. It is also shown in Figure 5.7 that when used as sand substitution, grow in the substitution degree of wood powders caused an appreciable increment in cement mortars' compressive strength. However, it should not be forgotten that sand is being systematically replaced with another inert material, wood powder. Therefore, the increment beheld in compressive strength of cement mortars are primarily imputed to finer particle size and hence the filler impact of wood powders used in this thesis.

5.5.1.2 Compressive strength of cement mortars combined wood fibre

Cement mortars are then combined with wood fibres and are employed both as cement and sand substitution herein. Compressive strength of cement mortars combining wood fibres both as cement and sand substitutions are shown in Figure 5.8. Figure indicates that using wood fibres as cement and sand substitutions in cement mortars caused a systematic reduction in compressive strength. The decline observed in mortars compressive strength are mainly due to weak bonds that fibres make with the matrix. The weak bond at the interface of wood fibres within the cement matrix causes the overall increment in porosity which caused a dramatic reduction in the strength of cement mortars.

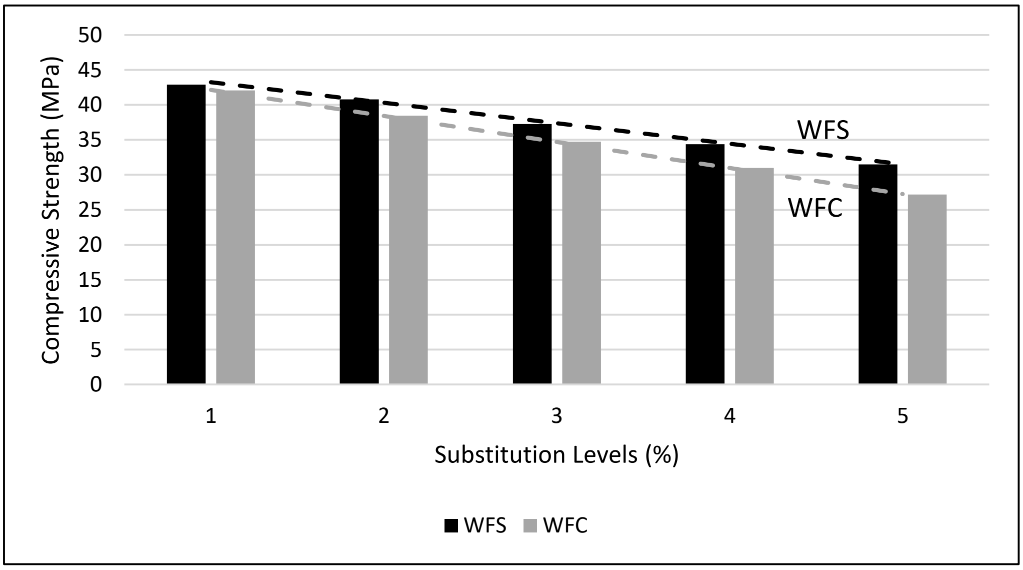


Figure 5.8: Compressive strength of cement mortars combined wood fibre used as, ■; sand substitute, ■; cement substitute

It must be further added to this section that the reduction observed in the compressive strength of concrete is in the range of approximately 30-35%. Inclusion of 5% wood fibre used both as cement and sand substitutions caused a 27 MPa and 32 MPa of compressive strength of mortars which could be used in various structural applications in construction practice.

5.5.1.3 Discussion

In Section 5.5.1, the compressive strength of cement mortars combining wood powder and wood fibres are investigated. These wood waste materials are employed as cement and sand substitutions in cement mortars. Inclusion levels were 1, 2, 3, 4 and 5%. Figure 5.9 shows the compressive strength of mortars combining wood powder and wood fibre as sand substitution. It is shown in Figure 5.9 that using wood powders in cement mortars causes an increment in the compressive strength however, when wood fibres are used as sand substitution, there is a steady reduction in the compressive strength of those mortars. Sand (an inert material) is being systematically replaced with another inert material sand here. Finer particle size of wood powders act as fillers in the matrix and therefore plays a key role in increasing the strength of cement mortar. The weak bond and therefore a weak interface that develops among the cement matrix and the wood fibres enhance the porosity and therefore an appreciable reduction in mortars’ strength.

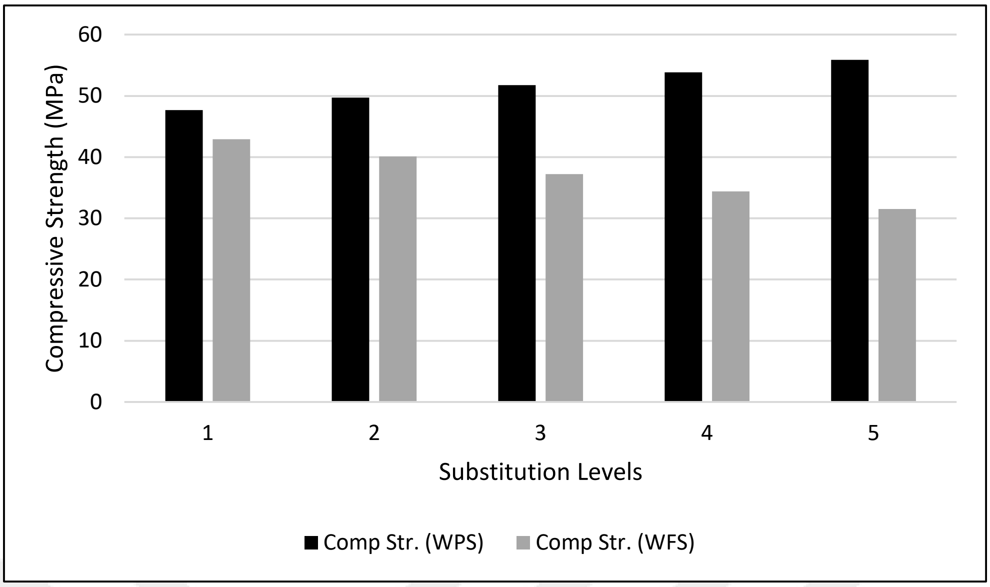


Figure 5.9: Compressive strength of cement mortars combining ■; wood powder, ■; wood fibre as sand substitution

Although a diminishment in compressive strength of mortars combining wood fibre is observed, it must be emphasized that 30 MPa of a compressive strength of cement mortars (the greatest reduction in compressive strength) is still high enough to be used for structural purposes in construction industry.

5.5.2 Flexural Strength

Flexural strength of cement mortars with increasing substitution levels of wood powder and wood fibres are addressed in this section.

5.5.2.1 Flexural strength of cement mortars combined wood powders

In this section, flexural strength of cement mortars combining wood powders used both as cement and sand substitutions is studied.

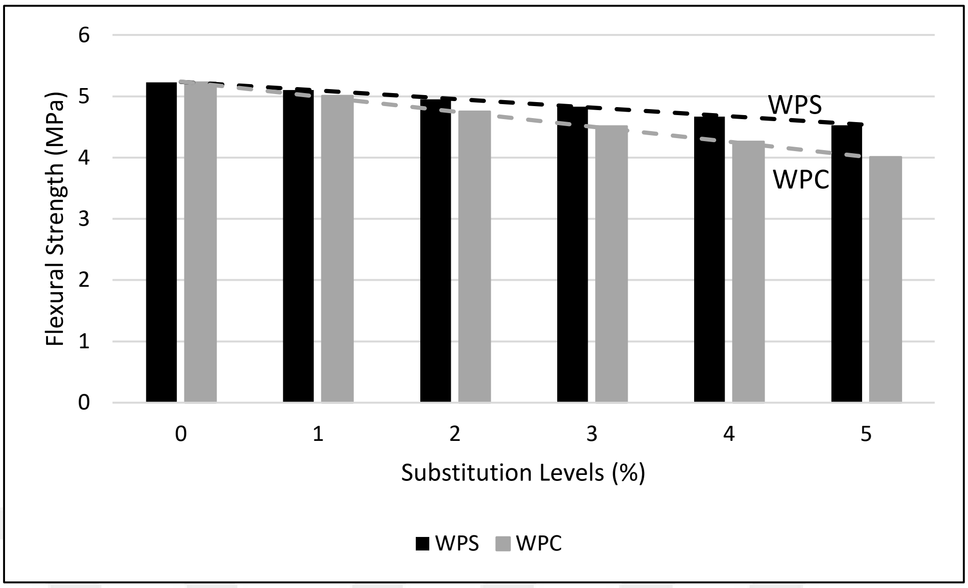


Figure 5.10: Flexural strength of cement mortar combining wood powders

Figure 5.10 demonstrates the increasing substitution levels of wood powders combined in cement mortars. Figure 5.10 shows that increment in the substitution level of wood powders used both as sand and cement substitution, inclined a minor reduction in flexural strength of cement mortars. Weak interface between the wood powders and cement paste is the main reason for such a reduction in flexural strength of cement mortars. Weaker zones and hence incremented air voids at the interfaces between the wood powders and cement paste tends to fail under flexure at a lower loading point which causes a decline in flexural strength. Greater reduction of mortars' flexural strength when combining wood powders into the cement mortars as cement substitutions were observed. In this case, reduction in the amount of cement content and hence reduction in the hydraulicity of the mixture coupled with the presence of weaker interface zones caused a major decline in flexural strength of cement mortars.

5.5.2.2 Flexural strength of cement mortars combined wood fibres

Figure 5.11 demonstrates the influences of the increasing substitution levels of wood fibres on the flexural strength of cement mortars.

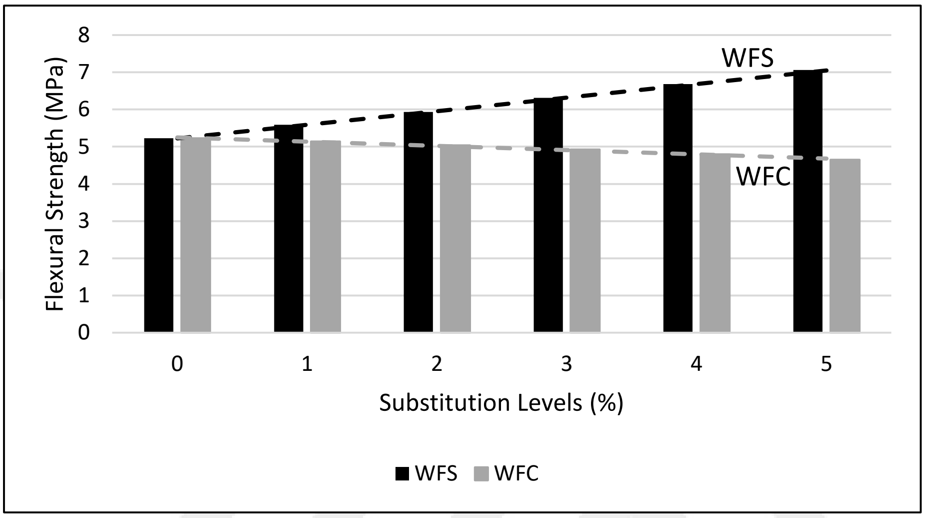


Figure 5.11: Flexural strength of cement mortar combining wood fibres

Although very small, a slight decline in flexural strength of cement mortars when combined wood fibres as cement substitution is observed. This is mainly as a result of the reduced amount of cement in the mix that was partially replaced with a non-hydraulic (inert) and coarser material. It is also observed in Figure 5.11 that increment in the wood fibre level used as sand substitution caused a noticeable increment in the flexural strength of cement mortars. In this case, an inert material, sand, is being systematically replaced with another material (wood fibre). It must be noted however that combining wood fibres in cement mortars improved the flexural strength of these materials. Fibres played a great role in preventing/delaying the developments of cracks. Presence of these fibres in the matrix were bridging the micro-cracks and were holding them in position avoiding and/or delaying the formation and progression of major cracks. This behaviour enhanced the flexural strength of cement mortars significantly.

5.5.2.3 Discussion

This section is reporting the influences of using wood powder and wood fibre on the flexural strength of cement mortars. It can be seen in Figure 5.11 that combining wood powders (either as a cement or sand substitution) did not improve the flexural strength of cement mortars. This was anticipated as wood powder formed a weak interface zone within the cement matrix under the effect flexural loads.

Wood fibres used as sand substitution levels were found to be the only combination effective in increasing the flexural strength of cement mortars. Wood fibres were bridging the cracks at the initial stages under the effects of flexure and increasing the flexural strength of cement mortar combined with wood powders used as a substitution level of sand.

5.5.3 Water Penetration Depth

Water penetration depth of cement mortars combining wood powder and wood fibres are addressed in this section.

5.5.3.1 Water penetration depth of cement mortars combined wood powders

Water penetration depth of cement mortars combining wood powders both used as sand and cement substitutions are studied in this section. To gain an insight into the influence of wood powders on water penetration depth of cement mortars, the porosity measurement is also conducted.

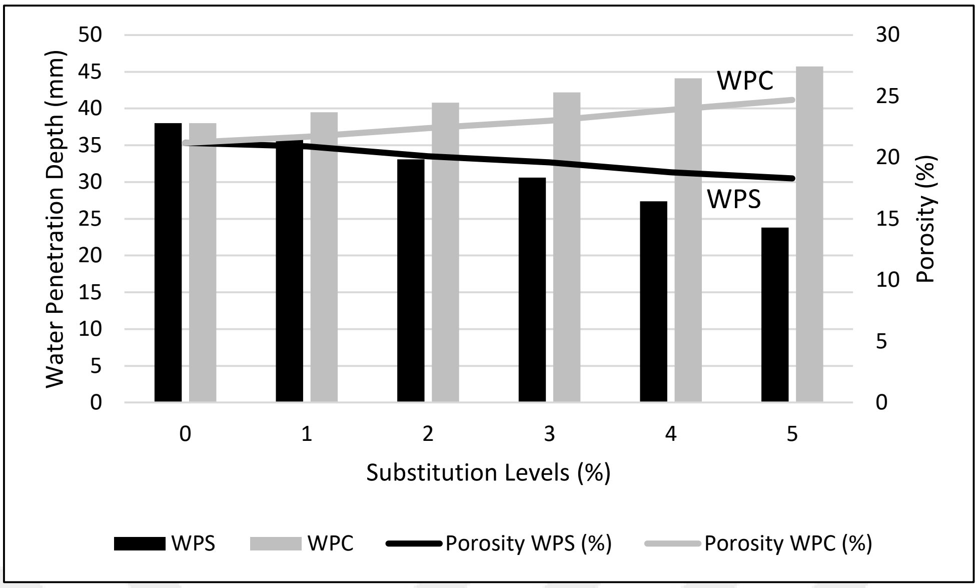


Figure 5.12: Water penetration depth of cement mortars combined wood powders

Secondary axis demonstrates the porosity (%) for cement mortars combining wood powders.

Figure 5.12 shows that increment in the substitution level of wood powders, used as cement substitution, caused a regular increment of water penetration depth of cement mortars. Increment observed in porosity with increment in wood powders, used as cement substitution, is in a proper compliance with the water penetration depth measurements of cement mortars. Hydraulic binder, cement is being systematically replaced with an inert material wood powders here and hence preventing the full hydration reaction to be conducted and therefore resulting in a more porous microstructure of these mortars that result also in an increment in water penetration depth.

On the other hand, increment in the substitution level of wood powders employed as a sand substitution in cement mortars caused a regular reduction in water penetration depth and a regular reduction in porosity of these mortars. In here, an inert material sand is being replaced with another inert material, wood powder. So the particle size effect played a great role in decreasing the water penetration depth. İncrement in the particle size and hence increment in the surface of fine materials, resulted in a less porous, denser microstructure that caused a decline in porosity and a decline in water penetration depth of cement mortars.

5.5.3.2 Water penetration depth of cement mortars combined wood fibres

Figure 5.13 shows that the use of wood fibres as cement and sand caused an increment in water penetration depth. When the porosity results are plotted in the secondary axis, it is also observed that inclusion of wood fibres caused regular increment of porosity of cement mortars. This was expected due to the inert character of the wood fibres. Fibres also could not develop a strong bond with the cement paste within the matrix and possible these are the reasons for the increment in porosity. However, the increment seen in porosity is not dramatic but was sufficient enough to cause a minor increment in the water penetration depth of cement mortars combining wood fibres employed both as cement and sand substitutions.

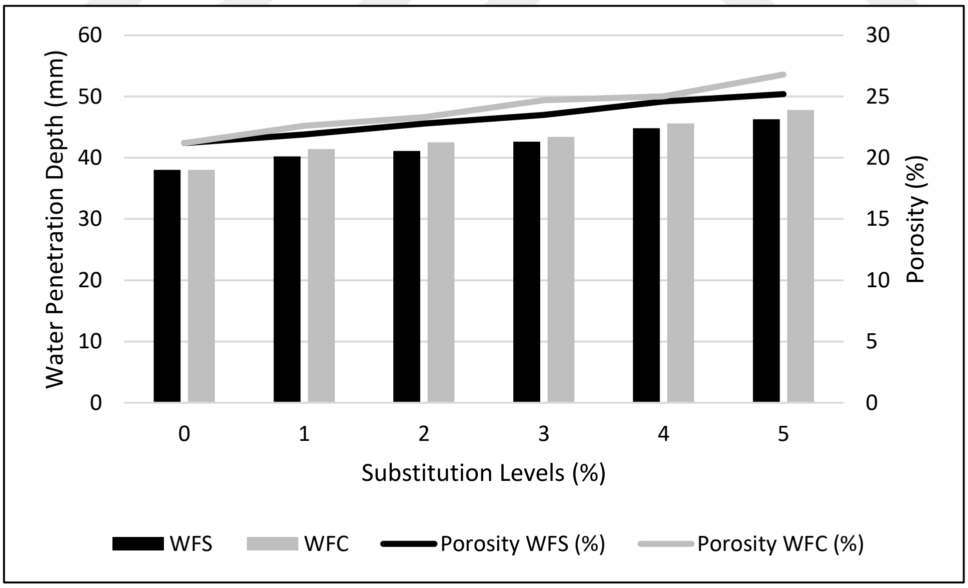


Figure 5.13: Water penetration depth of cement mortars combining wood fibres.

Secondary axis demonstrates the porosity (%) for cement mortars combining wood fibres

5.5.3.3 Discussion

Water penetration depth and sorptivity play a great role in the determination of the mechanical properties as well as the durability of cement based materials. It can be seen in the abovementioned results that apart from the wood powders used as cement substitution, waste wood inclusion in cement mortars does not improve its physical properties and in fact, is causing a minor increment in water penetration depth and porosity of cement mortars. When wood powders are used as sand substitution however, the finer particle size of the waste material leads to a denser and a less porous cement matrix to develop and therefore is resulting in a significant decline in water penetration depth of cement mortars.

5.5.4 Sorptivity

Sorptivity of cement mortars combined wood powder and wood fibre used as both sand and cement substitution is reported in this section.

5.5.4.1 Sorptivity of cement mortars combined wood powders

Sorptivity of cement mortars combined wood powders used both as cement and sand substitutions are reported in this section.

Table 5.3: Sorptivity of cement mortars combining wood powders

Substitution Levels (%)	WPS	WPC
1	0,132	0,154
2	0,128	0,160
3	0,123	0,165
4	0,119	0,172
5	0,113	0,179

Table 5.3 demonstrates that the rise in the substitution level of wood powders, used qua sand substitution, inclined a reduction in sorptivity of cement mortars due to the filler effect of wood powders. On the other hand, when wood powders are employed as cement substitution, sorptivity of cement mortars showed an increment. The consequence of this occurrence is already discussed in detail in Section 5.5.3.1. Replacing wood powders as sand substitution is effective in densifying the cement matrix and therefore is leading a considerable reduction in porosity and water penetration depth and henceforth causing substantial reduction in sorptivity of cement mortars.

5.5.4.2 Sorptivity of cement mortars combined wood fibres

Sorptivity of cement mortars combined wood fibres used both as cement and sand substitutions in cement mortars are reported in this section.

Table 5.4: Sorptivity of cement mortars combined wood fibres

Substitution Levels (%)	WFS	WFC
1	0,159	0,166
2	0,167	0,173
3	0,172	0,181
4	0,178	0,19
5	0,186	0,197

As it is largely discussed at the above section (Section 5.5.3.2), inclusion of wood fibres caused an appreciable increment in both the water penetration depth as well as in the porosity of cement mortars due to the inert character and a weak bond that develop between the fibres and the matrix. It is not at all surprising from this end that the increment in the substitution level of wood fibres, used both as cement and sand substitutes, caused systematic increment for sorptivity of cement mortars.

5.5.4.3 Discussion

Figure 5.14 demonstrates the sorptivity of cement mortar as well the sorptivity of cement mortars combining 3% of wood powders and wood fibres employed both as sand and cement substitute. It can be seen in this figure that only the sorptivity value of cement mortars combining wood powders as sand substitution has a lower value of the sorptivity of cement mortars along.

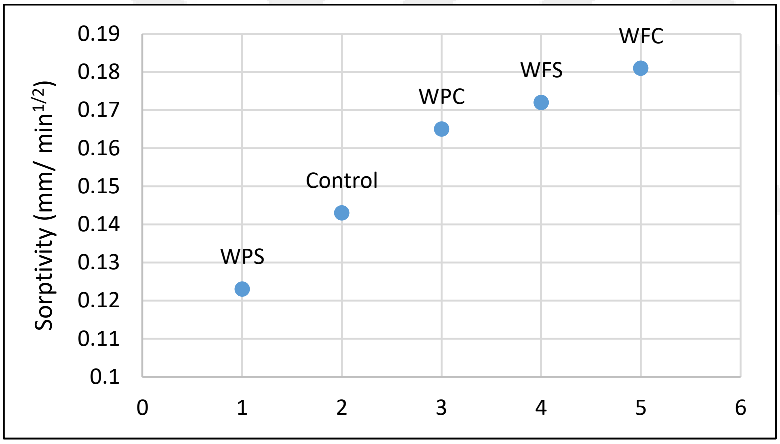


Figure 5.14: Sorptivity of cement mortars combining 3% waste wood

Sorptivity versus the water penetration depths of cement mortars combining wood powders as sand substitutions are plotted in Figure 5.15. It is clearly seen in this figure that the increment substitution levels of wood powders are systematically decreasing the sorptivity as well as decreasing water penetration depth of cement mortars. As discussed previously, this behaviour is a consequence of the filler effect of wood powders that leads to a denser and a less porous cement matrix to develop.

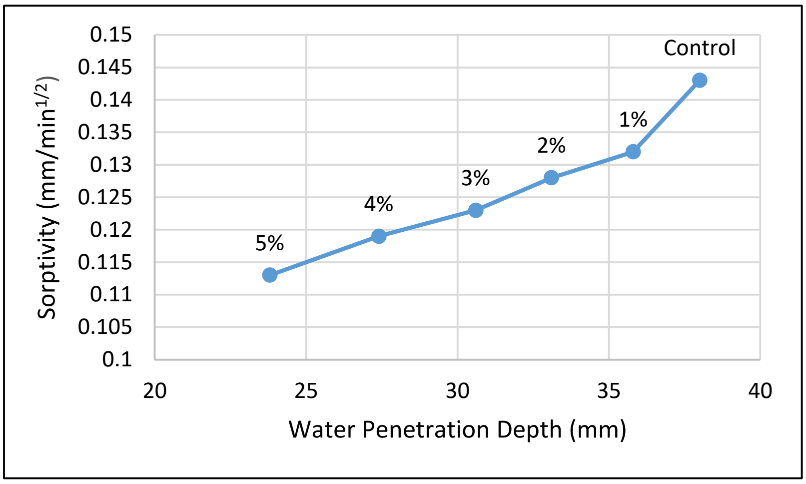


Figure 5.15: Water penetration depth and sorptivity comparison of cement mortars combined wood powder as sand substitution

5.5.5 Porosity

Porosity of cement mortars combined wood powder and wood fibre used both sand and cement substitution is reported in this section.

5.5.5.1 Porosity of cement mortars combined wood powders

This section reports the porosity of cement mortars combined wood powders used both as cement and sand substitutes in cement mortars.

Table 5.5: Porosity of cement mortars combined wood powders

Substitution Levels (%)	WPS	WPC
1	20,9	21,7
2	20,1	22,4
3	19,6	23
4	18,8	23,9
5	18,3	24,7

Table 5.5 shows that rise in the substitution level of wood powders, used as cement substitutes improves the porosity whereas the same increment in this waste wood reduces the porosity of cement mortars.

5.5.5.2 Porosity of cement mortars combined wood fibres

This section reports the porosity of cement mortars combining wood fibres used both as cement and sand substitutions in cement mortars.

Table 5.6: Porosity of cement mortars combined wood fibres

Substitution Levels (%)	WFS	WFC
1	21,9	22,6
2	22,8	23,3
3	23,5	24,7
4	24,6	25
5	25,2	26,8

Table 5.6 demonstrates that increment in the substitution level of wood fibres used both as cement and sand substitutes caused an increment for the porosity of cement mortars.

5.5.5.3 Discussion

Porosity, an important physical property of cement mortars, are already addressed in Section 5.5.3. In order to gain an insight into the influence of these wastes on the porosity of cement mortars, Figures 5.16 and 5.17 are plotted.

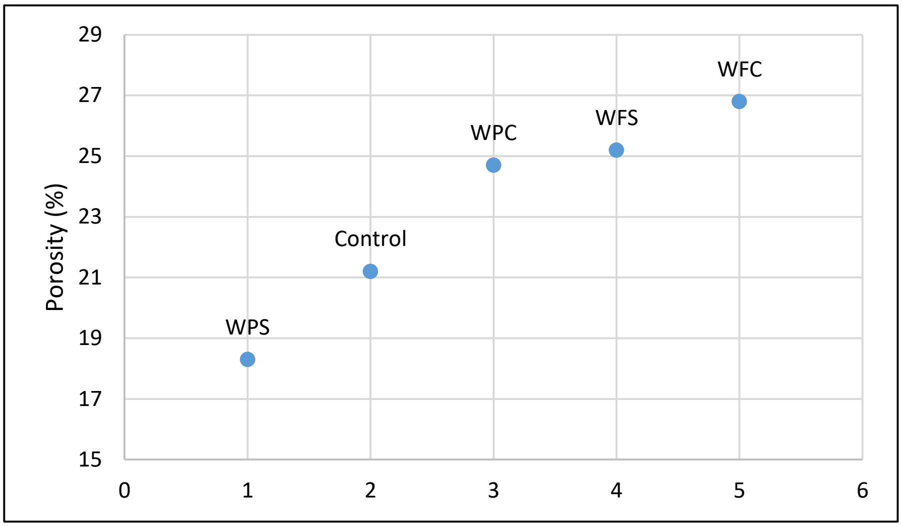


Figure 5.16: Porosity of cement mortars combining 5% waste wood

Figure 5.16 shows the porosity of cement mortar as well the porosity of cement mortars combining 5% of wood powders and wood fibres both as sand and cement substitute. It can be seen in this figure that only the porosity value of cement mortar combining wood powders as sand substitute has a lower value than the porosity of cement mortars along. This shows clearly that the use wood powders as sand substitution is most effective in decreasing the porosity of these mortars.

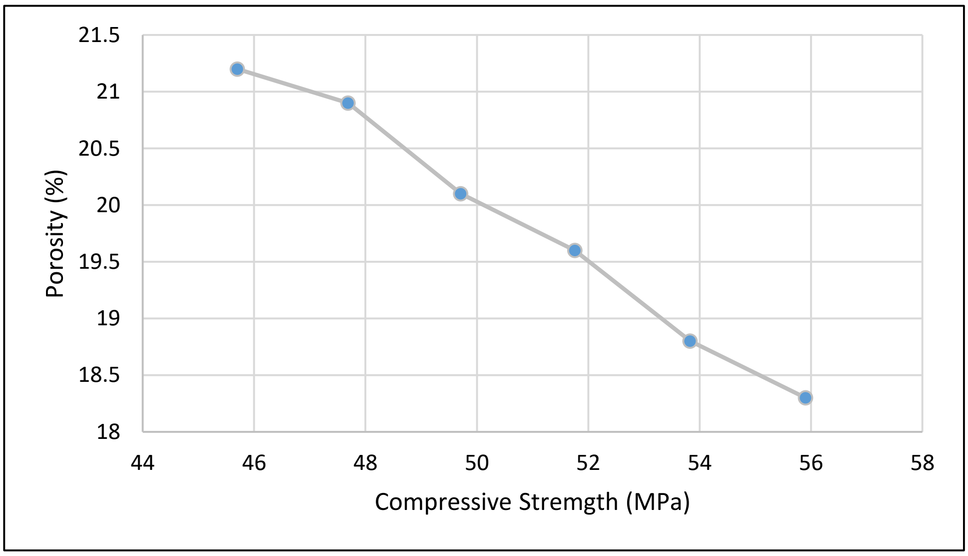


Figure 5.17: Compressive strength versus porosity of cement mortars combined wood powders as sand substitution

Porosity versus the compressive strength of cement mortars combining wood powders as sand substitutions are plotted in Figure 5.17. It is clearly seen in this figure that the increment substitution levels of wood powders, used as sand substitution, are systematically decreasing the porosity, resulting in a denser and therefore a less porous matrix to form which obviously enhances the compressive strength of cement mortars.

5.6 Durability Characteristics

Durability of cement mortars combining wood powders and wood fibres are examined by their resistance to freeze and thaw in this section.

5.6.1 Resistance to Freeze and Thaw

This section reports the freeze and thaw resistance of cement mortars combining waste wood.

5.6.1.1 Resistance to freeze and thaw of cement mortars combined wood powders

Freeze and thaw resistance of cement mortars combining wood powders used as both cement and sand substitutions in cement mortars are reported in this section.

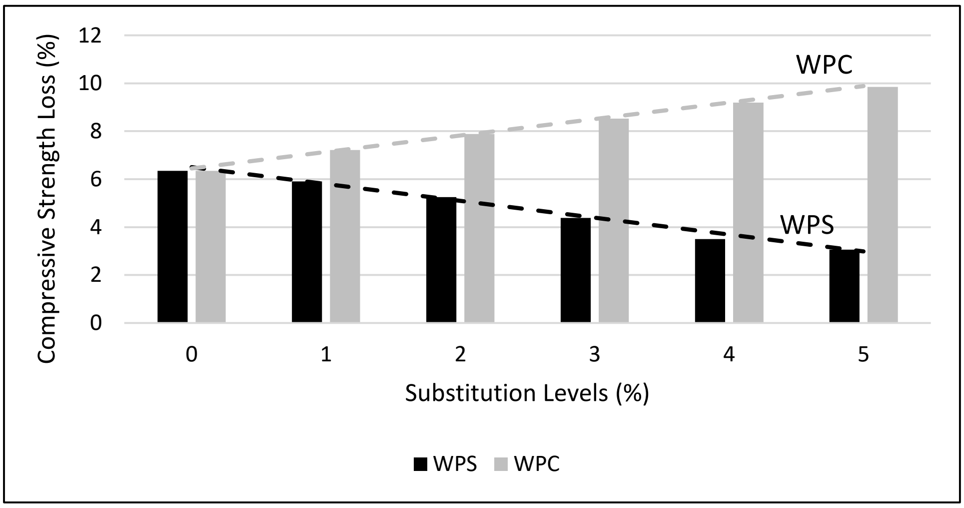


Figure 5.18: Resistance to freeze and thaw of cement mortars combined wood powders

Figure 5.18 shows the compressive strength loss of cement mortars exposed to freeze and thaw cycle. In this section, specimens containing wood powders employed as cement and sand substitutes are examined. Figure 5.18 shows that increment in the substitution level of wood powders used as sand substitutes caused a decline in the compressive strength loss of these mortars whereas this situation is reverse when wood powders are used as cement substitutions. The reduction observed in compressive strength loss of cement mortars made by using wood powders as sand substitutions indicates higher resistance to freeze and thaw cycles. It was previously shown that combining wood powders as sand substitutes caused a reduction in porosity as well as an increment in the strength of cement mortars. Freeze and thaw action is purely a physical condition and therefore, a significant reduction in porosity as well as an increment in strength resulted in an enhance resistance to freeze and thaw of cement mortars.

It is also shown previously that combining wood powders as cement substitution does not improve its physical properties and in fact, it is shown in Figure 5.18 that increment in the substitution level of wood powders used as cement substitute is caused an increment in the compressive strength loss of these mortars. This clearly indicates that they have a lower resistance to freeze and thaw action compared to the use of these wastes as sand substitution.

5.6.1.2 Resistance to freeze and thaw of cement mortars combined wood fibres

This section reports the freeze and thaw resistance of cement mortars combining wood fibres used as both cement and sand substitutions in cement mortars.

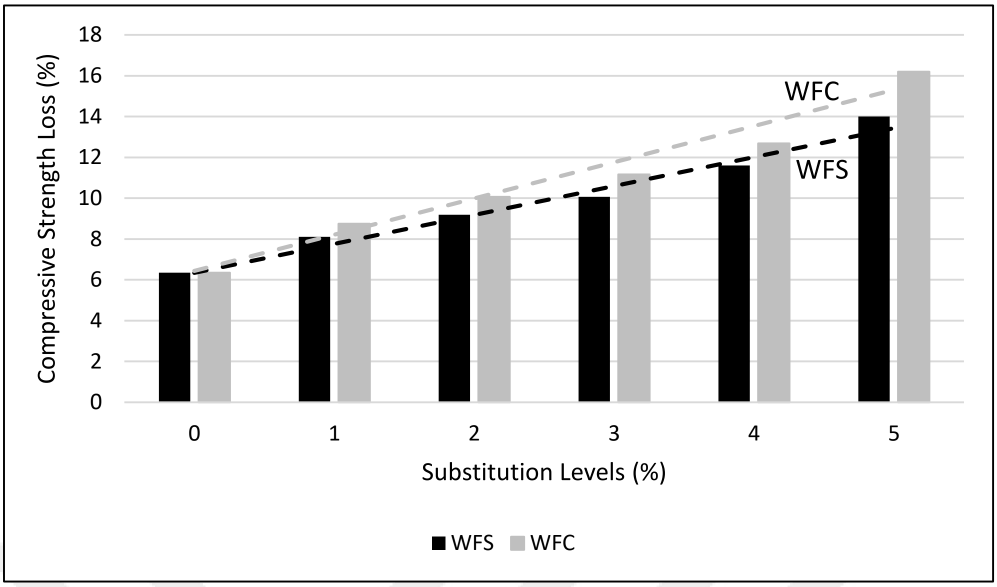


Figure 5.19: Resistance of cement mortars to freeze and thaw combined wood fibres

Like it is previously reported in the thesis, combining wood fibres in cement matrix often resulted in an increment in the porosity of the mortars. The increment in the porosity of cement mortars have reflected in the results shown in Figure 5.19 as porosity of these materials govern the resistance to freeze and thaw action solely. Increment in porosity of these mortars in fact, caused an increment in compressive strength loss of cement mortars combining wood fibres. This means in other words that when cement mortars are combined with wood fibres, regardless of their substitution type, their resistance to freeze and thaw action is reduced.

5.6.1.3 Discussion

Figure 5.20 shows the compressive strength loss of cement mortars with respect to the increment in substitution levels of wood powders used as sand substitution only. Expansion determined in (%) is also plotted in the secondary axis. Figure 5.20 demonstrates that increment in the substitution level of wood powders used as sand substitution does not only result in a substantial decline in the compressive strength loss of these mortars but also leads a significant reduction on the expansion. Reduction in compressive strength coupled with a reduction in expansion of these mortars clearly indicates that combining wood powders used as sand substitution were effective in increasing the resistance of these materials to freeze and thaw action.

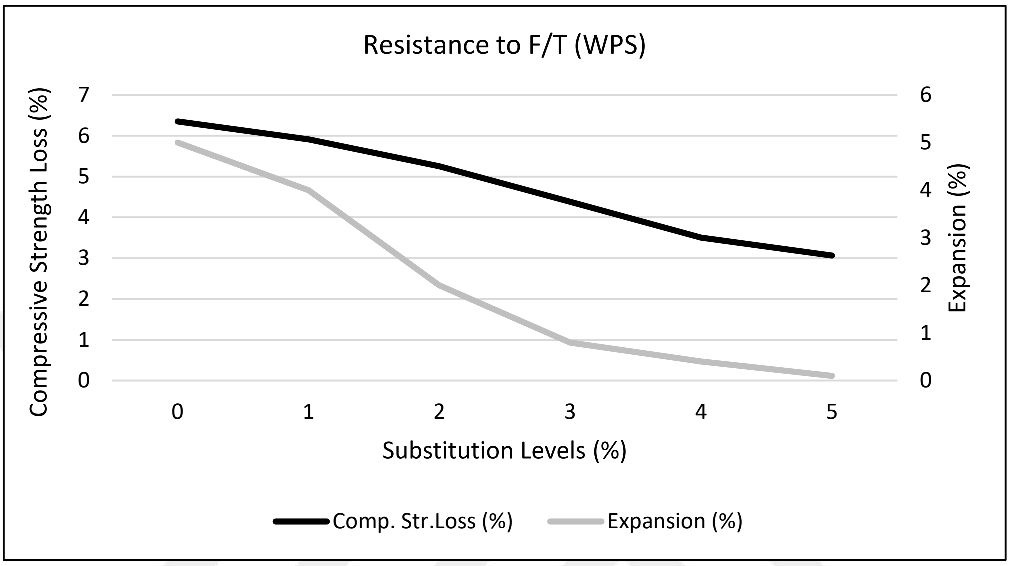


Figure 5.20: Compressive strength loss versus expansion of cement mortars combining wood powders used as sand substitution

5.7 Cost Effectiveness

Cost effectiveness factor of cement mortars combining wood powders employed both as sand and cement substitution materials is examined in this section. Cost effectiveness is determined simply using the following equation:

$$Cost\ effectiveness = \frac{Strength}{Cost}\ x\ 100 \qquad\qquad Eq. (1)$$

In order to find the cost of these mix constituents, quantities used to produce 1 m^3 of cement mortar are re-calculated. Consumption of cement is expressed in kg/m^3 and consumption of sand is expressed in m^3. Local prices of the Northern Cyprus in the period of the study are used to calculate the cost. \$0.12 is taken as the unit price for cement for 1 kg and \$14.86 is taken for 1 m^3 of fine aggregates. Total cost is simply obtained by summing the cost of cement and cost of fine aggregates.

The mix constituents, cost of mix constituents and strength values of cement mortar combining wood powder both as cement and sand substitution are shown in Tables 5.7 and 5.8, respectively. Cost efficiency of these mortars are then calculated using Eq. (1).

Table 5.7: Cost effectiveness of cement mortar combining wood powder used as cement substitution

Type of mortar	Cement (kg/m^3)	Sand (m^3)	WPC (ton/m^3)	Cost of Cement ($)	Cost of Sand ($)	Total Cost ($)	Strength (MPa)	Cost Effectiveness (%)
Control	1140	0,849	-	136,8	12,616	149,416	45,7	30
CEM+1% WPC	1116,3	0,849	23,7	133,95	12,616	146,566	43,01	29
CEM+2% WPC	1092,6	0,849	47,4	131,11	12,616	143,726	40,3	28
CEM+3% WPC	1068,9	0,849	71,1	128,26	12,616	140,876	37,57	26
CEM+4% WPC	1045,2	0,849	94,8	125,4	12,616	138,016	34,82	25
CEM+5% WPC	1021,5	0,849	118,5	122,58	12,616	135,196	32,1	23

It can be seen in Table 5.7 that combining wood powders as a cement substitution did not improve the cost efficiency of cement mortars. The cost efficiency of control mortar (cement mortars that do not contain wood powders) was calculated to be 30%. Cost efficiency of cement mortars are found to be systematically decreasing with the increment in replacement level of wood powders used as cement substitutions.

Although replacing cement using a wood waste reduced the total cost of the mixture considerably, the reduction observed in strength was predominant and hence was the governing parameter in decreasing the cost efficiency of these mortars.

It should not be forgotten that even at the highest substitution level of wood powder (5% cement substitution) the compressive strength that is achieved, 32 MPa, is still quite high for structural concrete and hence can be used as load-bearing members in structures. When the cost efficiency is re-analysed knowing that 32 MPa is an acceptable strength for structural concrete, it can be concluded that although the structural performance of cement mortar combining wood powders are not improved, requirement of cement as well as the total cost of such mortars are reduced significantly. This suggests that there will be a significant reduction in the consumption of cement (and a significant reduction on the embodied energy) as well as a considerable reduction on the CO_2 emission.

Table 5.8: Cost effectiveness of cement mortar combining wood powder used as sand substitution

Type of mortar	Cement (kg/m^3)	Sand (m^3)	WPS (ton/m3)	Cost of Cement ($)	Cost of Sand ($)	Total Cost ($)	Strength (MPa)	Cost Effectiveness (%)
Control	1140	0,849	-	136,8	12,616	149,416	45,7	30
CEM+1% WPS	1140	0,798	22,5	136,8	11,858	148,658	47,69	32
CEM+2% WPS	1140	0,748	42,6	136,8	11,115	147,915	49,71	33
CEM+3% WPS	1140	0,74	63,9	136,8	10,996	147,796	51,76	35
CEM+4% WPS	1140	0,651	75,8	136,8	9,674	146,474	53,83	36
CEM+5% WPS	1140	0,643	94,8	136,8	9,555	146,355	55,9	38

Cost efficiency of cement mortars combining wood powders as sand substitute are summarised in Table 5.8. It can be seen that increment in the substitution level of wood powders used as sand substitutions, systematically incremented the cost efficiency of cement mortars. The results have shown previously that, replacing sand with wood powders results in a denser and less porous system which improves the strength of cement mortars. Dramatic increment in strength coupled with a slight reduction in the total cost caused an appreciable increment in the cost efficiency of these mortars.

The results reported in Table 5.8 indicate that the consumption for the raw materials, sand, can be significantly reduced and hence energy spent on extracting, cutting and sieving could be saved. This is also suggests that higher structural performance of cement mortars can be achieved when wood powders are used as sand substitution. İncrement in the structural performance would allow the use of cement mortars in a more variety applications in structures.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

The thesis is addressing the use of waste wood in cement mortars. Waste wood namely; wood powders and wood fibres are used both as cement and as sand substitute materials in cement mortars. Mix design principles are used to obtain the mix constituents used in the experimental part of the work. Characterisation study conducted using X-Ray Fluorescence and particle size distribution analysis allowed the substitution types and substitution levels of waste wood to be determined. Characterisation study also enlightened the understanding of the behaviour of the cement mortars combining wood powders and wood fibres. Consistency and setting time of cement mortars combining both wood powders and wood fibres are obtained to determine the fresh properties of these mortars. It is reported in the thesis that although the inclusion of wood powders reduced the consistency of cement mortars, combining wood fibres caused a slight increment in the consistency of these mortars. Although not dramatic, it was reported in the thesis that increment in the substitution levels of wood powders and wood fibres (used both as cement and sand substitutes) caused an increment in the setting time of cement mortars. It was also discussed in this thesis that saturation process was not found effective in saturating the powders and fibres and in fact this process was found to increment the water content and therefore the water cement ratio of the mixture and hence was decided not to adopt in this thesis.

Mechanical properties of cement mortars combining wood powders and wood fibres are also studied in the thesis. Compressive and flexural strength tests are conducted to determine the mechanical properties of cement mortars examined in this thesis.

Due to its filler effect, wood powders used as sand substitutions were the only combination that improved the compressive strength of cement mortars. Although not dramatic, other combinations examined in this thesis caused a reduction in compressive strength of cement mortars. It should not be forgotten that the lowest compressive strength of cement mortars observed in the study was approximately 27 MPa could be acceptable to be used for construction applications.

When the flexural strength of cement mortars was evaluated, it was found that wood fibres used as sand substitution were the most effective in enhancing this capacity. Wood fibres were bridging the cracks and improving the flexural capacity of these mortars.

Physical properties such as water penetration depth, sorptivity and porosity of cement mortars combining wood powders and wood fibres were measured. It is reported in the thesis that wood powder inclusion was often found to be very effective in densifying the matrix and therefore usually the use of wood powders particularly in sand substitution in cement mortars resulted in a considerable decrease in water penetration depth, sorptivity and porosity of these mortars.

Durability of cement mortars containing wood powders and wood fibres are determined by measuring their resistance to freezing and thawing action. Freezing and thawing action was artificially created in the laboratory environment. Specimens that contain wood powders and wood fibres (used both as cement and sand substitutions) were located in the freeze and thaw chamber and 2 consecutive cycles were done in 1 day where the temperature carried from -30°C to +30°C and relative humidity was approximately 30%. It was found in the thesis that cement mortars combining wood powders employed as sand substitutions had the highest resistance against freeze and thaw resistance. This was attributed to their dense microstructure, reduced porosity and incremented strength that enhanced the resistance against freeze and thaw action.

Cost effectiveness factor which is the strength to cost ratio of cement mortars containing wood powders used both as cement and sand substitutes were also calculated. Results show that cost effectiveness factor is increasing with the increment substitution levels of wood powders employed as sand substitutions due to the increment in strength and a slight reduction in the total cost.

It was found out that combining wood powders in cement mortars as cement substitutes does not improve the cost effectiveness factor. This is mainly because of the reduction observed in compressive strength values of cement mortars containing wood powders. When the compressive strength values are closely examined, it was noticed that the lowest compressive strength observed was 5% wood powders as cement substitutions is even still quite a high value of strength which can be used in the construction practice.

It was observed that when wood powders were used as sand substitution, most of the parameters examined in this thesis such as compressive strength and freeze and thaw resistance, reached their highest values at the replacement level of 5%. For example, compressive strength of the control sample was 45,7 MPa whereas the mortars substituted with wood powders as 5% sand replacement was 55,9 MPa at the end of 28 days. In the same way, freeze and thaw resistance of the cement mortars which was measured as compressive strength loss, has decreased from 6,35 to 3,06 that means the F/T resistance has increased. These results are in compliance with the decrease in the water penetration depth, sorptivity and porosity of the cement mortars combined wood powders as sand replacement.
It is important to note that the use of wood powders both as cement and sand substitutions results in a reduced necessity of raw materials to produce these mortars. This is also significantly reduces the total cost of these materials. But more importantly, the reduction in the consumption of raw materials (both cement and sand) significantly reduces the embodied energy (required to manufacture and/or extract, cut and sieve) as well as reduces the CO_2

emissions generated during the manufacturing of these materials. Incorporation of 5% WPC results in 10.2% reduction of the cement consumption when $1m^3$ of mortars are constructed. This is equivalent also to approximately 10% reduction of the CO_2 emissions required for the cement manufacturing. Considering that cost of 1 ton of carbon sequestration is 40USD, 10% reduction of CO_2 emissions, simply by incorporating the waste wood powder in cement, would reduce this figure to 36USD by itself.

To sum up, the results found in this thesis suggests that the inclusion of these waste materials more specifically the use of wood powders, can improve the mechanical properties and physical features of cement mortars. The combinations that does not improve the mechanical properties of cement mortars still produces high enough strength to be used in structural purposes in construction practices. So the use of these wastes in cement mortars considerably reduces the need for the raw materials in making mortars. This results in a reduced embodied energy, reduced CO_2 emissions as well as results in a more cost effective material to be formed.

It can be concluded from this study that, the combinations made with sand replacements showed better behaviour with respect to cement replacements in terms of mechanical and physical properties as well as durability characteristics of the mortars. This can be attributed to the replacement of a hydraulic material, cement, with a non-hydraulic material, wood waste.

On the other hand, the use of waste wood in cement mortars strongly suggests a sustainable waste management approach for this waste. Particularly for developing countries such as North Cyprus, adopting this approach is believed to make a significant improvement on the waste management of wood powders and fibres as well as suggests a greener cement mortars to be developed for construction practice.

6.1. Future Suggestions

The suggestions that are given in this thesis are followed:

1. In order to make a stronger bond between the fibres and powders with cement paste, it may be important to adopt one of the treatment techniques for this type of waste to improve its surface texture/characteristics. When the surface texture of this waste can be treated, it is expected to make stronger bond with the cement hydration products and therefore make a stronger matrix in general.

2. In order to improve both the mechanical properties and physical properties of cement mortars combining waste wood, use of pozzolans coupled with this waste can be considered. The use of pozzolans can also allow higher substitution levels of such waste in cement mortars without altering the mechanical properties of these mortars.

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