REUSING WASTE FOUNDRY SAND AS FINE AGGREGATE IN CONCRETE FOR PAVING BLOCKS

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DECLARATION

I, Esther Momanyi, do declare that this report is my original work except to the extent cited herein and to the best of my knowledge, it has not been submitted for any degree award in any University or Institution.

Signed____ Date ____________
Esther Momanyi

Supervisors
I have read this report and approve it for examination

Signed____Date_____________
Prof. Z.A. Gariy

I have read this report and approve it for examination

Signed____Date_____________
Prof. R.N. Mutuku

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LIST OF ABBREVIATIONS

FIRST- Foundry Industry Reuse Starts Today
HMA – Hot Mix Asphalt
KAM – Kenya Association of Manufacturers
MoSPND – Ministry of State Planning and National Development
OPC – Ordinary Portland cement
ReTAP - Recycling Technology Assistance Partnership
WFS – Waste Foundry Sand

ABSTRACT

Acquisition of natural sand for construction and disposal of industrial by-products is becoming unattractive worldwide due to their associated negative economic and environmental impacts. The option of re-using Waste Foundry Sand (WFS) as fine aggregate in concrete offers benefits to both construction and industrial sectors. The present study aimed at investigating the re-use of WFS as replacement fine aggregate in producing concrete paver blocks that meet the quality standard specified in BS EN 1338:2003 and in ASTM 1988. The study assessed the physical and chemical properties of Green and Chemically Bonded WFS obtained from East Africa Foundries Ltd and Numerical Machining Complex, both in Nairobi, Kenya. It also investigated the separate effects of the two types of WFS in equal proportions as partial replacement of fine aggregates at 0%, 5%, 10%, 20%, and 30% on concrete properties such as compressive strength, tensile strength and water absorption, from which the optimal proportion of WFS was determined.

The results showed that Natural sand, Green and Chemically Bonded WFS used are in grading zones II, III and IV respectively and that the two types of WFS have different chemical compositions. The water absorption of the concrete paver blocks containing different proportions of WFS was comparable to those of the control mix, with a range of 4.3-4.6% by mass. The 28 days tensile strength was in the range of 3.50-3.78MPa and 3.15-3.73MPa for partial replacement with Green and Chemically Bonded WFS respectively while blocks from the control mix had the highest tensile strength of 3.79MPa. Similarly, the observed 28 days compressive strength was in the range of 50.2-55.2 MPa and 50.5-53.7MPa for Green and Chemically Bonded WFS respectively whereas blocks from the control mix had the highest compressive strength of 61.0MPa. Lastly, it was observed that in the blocks containing WFS, the highest tensile and compressive strengths were observed at 5% and 10% replacement for Green WFS and 20% and 10% replacement for Chemically Bonded WFS. In conclusion, the different performance of the two WFS types is due to their varied chemical composition whereas the higher strengths in the control mix are attributed

to the coarser particle size of natural sand relative to WFS. Nonetheless, the replacement of WFS from 5%-10% green WFS and 10%-20% chemically bonded WFS can make concrete paver blocks with, ≤6% by mass water absorption and 50MPa compressive strength at 28 days, which is the standard quality.Based on these study findings, the reuse of green or chemically bonded waste foundry sand as fine aggregate for high strength concrete such as making of concrete paver blocks is recommended at 5% to 10% of green WFS and 10% to 20% of chemically bonded WFS.

CHAPTER 1

Introduction

1.1. Background to the Study

Foundry sand is a by-product from the production of both ferrous and nonferrous metal castings. Foundry sands can have properties desirable for use in the technology of substituting fine aggregates in applications such as; structural fills or embankments, road base or sub base, hot mix asphalt (Odeyemi et al. 2015), flowable fills and manufacture of Portland cement (Goodhue et al. 2001, FIRST 2004). In foundry industries, the process of metal casting requires the use of high quality silica sands mixed with bentonite clay and water to make the outside shell of the mould cavity into which molten metal is poured (Gedik et al. 2008). Since metal casting has to be done at high temperature, sands are chosen as the mould cavity material because they have desirable characteristics. These include readiness to bond with clay, and high refractory nature, ability to retain mould shape during packing and pouring, permeability for the gases liberated from the mould and solidifying metal as well as ability of the sand to be shaken out (Bakis et al. 2006).

Excess foundry sand is generated since varying amounts of fresh sand, water and clay must be continually added to maintain the desired characteristics. This results to a larger volume of sand than is required for the foundry process (Goodhue et al. 2001). The excess sand is considered as waste because after repeated use under heat, the particles become degraded and cannot be used for the moulding process (ReTAP 1996). However, the fact that this sand can no longer be used for moulding does not render it completely useless, as it can find use in non-foundry applications. These include embankments/structural fills, road base/sub base, hot mix asphalt (HMA), flowable fills, soil/horticultural, cement and concrete products as well as traction control (FIRST 2004).

Since making of road bases is one of the non-foundry applications of Waste Foundry Sand (WFS), its reuse as aggregate in making concrete paving blocks has been identified for the present study. Concrete paver blocks are commonly installed as the base course of rigid pavements, footpaths, passenger waiting shades, bus stops, industrial parks and public places in the urban areas. Radhikesh et al. (2010) define concrete paving blocks as precast solid products made out of cement concrete, in various sizes and such shapes as rectangular, square, and round blocks of different dimensions with designs for interlocking of adjacent paving blocks. Aggregates form about 70-80% of the concrete constituents in the construction of both rigid and flexible pavements (Roberts et al. 1996, Waziri et al. 2011). Evidently, the proportion of aggregates in concrete is the highest of all the constituents. Therefore, abundant supply of aggregates is required for concrete applications, thus the need to explore the use of industrial waste products, including WFS as additional sources of fine aggregates. More so, the reuse of WFS has not been employed in Kenya yet. The selected industries, from which the present study samples were collected dispose there WFS to landfills. The collection and disposal of WFS is done by subcontractors who are licenced by the Nairobi City council. Therefore, WFS can be one of the additional sources of fine aggregate in Kenya, upon proof of satisfactory performance in the relevant applications.

Typically, the major generator of waste foundry sand is the automotive industry and its parts supplies. For example, in the United States, metal casting for the automotive industry and its parts supplies, uses about 95 million tons of foundry sand per annum. The main metals cast for this industry are iron and steel. Particularly, Monosi et al. (2010) assert that for each ton of iron or steel casting produced, about 1ton of foundry sand is employed. This quantity demonstrates that there is a profound impact of disposing of the foundry sand after use, hence the need to put the waste foundry sand into beneficial use.

One of the most important factors that determine the application of waste foundry sand is its quantity in a given location. According to FIRST (2004), the following applications of foundry sand, by ranking, based on the quantity used have been mentioned: embankments/structural fills, road base/sub base, hot mix asphalt (HMA), flowable fills, soil/horticultural, cement and concrete products as well as traction control. In close relation to quantity, the quality of WFS is also significant. FIRST (2004) stress that the raw silica sand for making foundry sand is normally of higher quality than typical bank run or natural sands used in construction. This indicates that even after use in the moulding process, the waste sand generated from the foundries will have properties that are comparable to those of typical bank run sand for construction applications.

1.2. Problem statement

There are increasing negative impacts associated with the acquisition of construction materials in Kenya. The mining and transportation of these materials from the source comes with a very high cost. In addition, the process of mining natural sand requires a lot of labour and time as well as causing air pollution by trucks as they transport the sand from the sand deposits and rivers to construction sites, especially in urban areas where demand for construction material is highest. In fact, the United States Environmental Protection Agency (USEPA) establishes that motor vehicle exhausts contain air pollutants such as ozone, carbon monoxide and nitrogen dioxide, which are harmful to human health. Also, overexploitation of sand deposits is an environmental problem as it leaves behind open pits which can become breeding grounds for mosquitoes when water accumulates therein. This creates a health hazard.

Another notable aspect of natural sand is that the deposits are not available everywhere in Kenya. As a result, the regions that do not have the sand deposits may suffer from lack of sand for construction if the people with the same decide to withhold the commodity and bar them from exploiting any of their reserves. This is a potential challenge in Kenya, especially with the advent of county governments. Particularly, there is already an increase the cost of accessing or mining sand resulting from the bid by counties to raise money from their county based resources. Therefore, the affected areas, which are mostly urban, need an alternative for sand in their construction. Also, the quantity of sand needed to make concrete for any application is one of the highest based on the fact that aggregates form about 70-80% of the concrete constituents in the construction of both rigid and flexible pavements (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996; Waziri, A. Mhammed, A.G.Bukar, & 21., 2011)

On the other hand, in the foundry industries, the waste sand generated is continually increasing thus creating a financial burden as more cost has to be incurred in disposal. This is because the industries are required to purchase land elsewhere for the disposal of their waste foundry sand. In particular, the two foundry industries visited during the study generate about 307 tonnes per annum. Consequently, with continued disposal, the landfills become saturated and the soil much polluted. Some industries even dispose the waste into rivers, which is a worse practice. This is attributed to the fact that the waste foundry sand contains organic and metal pollutants which threaten the life of flora and fauna. Further, the treatment of such water for domestic use becomes very expensive.

For the above reasons, there is need for more research on the re-use of waste foundry sand in pavement construction, as one of the identified non-foundry applications of WFS, with the aim of providing an alternative construction material. The reuse can minimize the impacts of mining and processing of virgin material and promote green construction.

1.3. Objectives

1.3.1. Overall objective

The overall objective of this study is to evaluate the use of waste foundry sand, as replacement aggregate in concrete for paving blocks.

1.3.2. Specific objectives

i. To determine the chemical composition of waste foundry sand generated from selected foundry industries in Nairobi.

ii. To assess the physical properties of waste foundry sand from various foundry industries in Nairobi.
iii. To evaluate the optimum percentage replacement of waste foundry sand as fine aggregate in concrete for paving blocks.

1.4. Research Questions

i. What are the chemical characteristics of waste foundry sand generated from major industries in Nairobi?
ii. What are the physical properties of waste foundry sand generated from foundry industries in Nairobi?
iii. What proportion of waste foundry sand was required to achieve optimum strength of concrete paving block material?

1.5. Significance of the Study

This study seeks to evaluate the use of waste foundry sand which is an industrial by-product that needs to be recovered with urgency. Foundry sand can be resourceful as a substitute or supplement for natural sand which is becoming scarce by the day. There is a high demand for pavements in urban areas but the availability of sand for their construction is limited. Therefore, the results of this study can be of benefit to the construction industry because the use of WFS as fine aggregate will offer a cheaper and convenient alternative as the material source will be close to the construction site in urban areas, where most foundry industries are located. This will in turn help reduce the negative impacts related to energy use, resource exploitation and environmental pollution. With the understanding that there is a rapid increase in the Kenyan population and the world at large, there is a consequent need for more land and better infrastructure. Therefore, the use of the existing resources needs more prudent planning so as to avoid a scenario where the future generations are not able to meet their needs. So, the practice of resource conservation has to start now.

1.6. Scope and Limitation of the Study

1.6.1. Scope of the study

Sand is a material that finds use in various applications such as making mortars and plasters, manufacture of glass and tiles, filtration of water, landscaping as well as being a constituent material in concrete. This study focuses on the substitution of natural sand with foundry sand only in making concrete paving blocks, as one of the many applications identified earlier in section 1.1. The choice of this particular application is based on the fact that any finished concrete product containing more than 5% foundry sand as fine aggregate will have a black or grey tint on it(Bhimani, Pitroda, & Bhavsar, 2013). This may not be appealing if the sand is used in such applications as making mortars, plasters, concrete beams or columns, unless an additional coating is applied. However, for the case of paving blocks the tint is not unsightly hence the consideration to use foundry sand in this application.

1.6.2. Limitations of the study

This study is limited to waste foundry sand obtained from selected foundry industries in Nairobi, Kenya. The Industries are East Africa Foundries Limited and Numerical Machining Complex.

Also, this study did not determine the durability of the concrete paver blocks through abrasion resistance test due to unavailability of the required equipment.

Lastly, due to time constraints, the study focused on determining the characteristics and performance of WFS based on only one factor, which is the additive used as binder material. This is among many aspects that may influence the performance of WFS, as explained in section 2.3.5.

CHAPTER 2

Literature Review

2.1. Introduction

This section contains an in-depth review on conventional aggregates and foundry sand. It highlights the classification of conventional aggregates as well as the description, generation and applications of waste foundry sand. Also, the results from previous studies on foundry sand applications have been compared and a research gap established.

2.2. Aggregates

2.2.1. Introduction

Aggregates are significant constituents in concrete. They give body to the concrete, reduce shrinkage and effect economy. Good gradation of aggregates is a key factor for production of workable concrete. A well graded aggregate sample contains various aggregate sizes in required proportions such that there are minimum voids. This reduces the amount of paste needed to fill up the voids in the aggregates. As a result, less quantity of cement and water is used, which enhance economy, higher strength, lower shrinkage and greater durability of the resultant concrete product (Prajapat, Joshi, & Pitroda, 2013). And so, any material used to replace aggregates in their various applications should possess similar characteristics.

2.2.2. Classification of Aggregates

Aggregates are variously classified on the basis of their grain size, origin and density as follows (Duggal 2003): Firstly, by grain size, there are fine aggregates with grain size between 4.75mm and 0.15mm and coarse aggregates that are retained on sieve of mesh size 4.75mm. Secondly, by origin, aggregates can be natural aggregates which are available and ready to use from natural sources such as sand from rivers, gravels from river banks, by-product aggregates which are obtained as waste products such as slag from blast furnaces or processed aggregates which are normally manufactured such as burnt clays for making light weight concrete. Lastly, by density, aggregates are classified as normal aggregates which include gravels, sand and crushed stone of density around 2300-2500kg/m^3; high density aggregates which are used as shields for radiation such as barite of density above 4000kg/m^3 or light weight aggregates which include natural and artificial materials of low density such as pumice, wood waste, wood waste, fly ash, slag and burnt clay of density around 350-750kg/m^3. The knowledge of this classification is essential in the present study for the analysis of the physical characteristics of WFS as fine aggregate, to establish how it compares with natural river sand.

2.3. Foundry Sand

2.3.1. Introduction

Foundry sand is high quality silica sand, which is used in the set up for production of ferrous and nonferrous metal castings. The sands form the outer shape of the mould cavity. These sands normally rely upon a small amount of binder material to create sand "cores" for the cavity formation (Foundry Industy Reuse Starts Today, (FIRST) 2004) .When the sand has been used repeatedly in the foundry system and the particles have degraded, it is discarded and replaced as explained earlier in Section 1.1.

2.3.2. Generation of Waste Foundry Sand

Typically, the major generator of waste foundry sand is the automotive industry and its parts supplies. For example, in the United States, metal casting for the automotive industry and its parts supplies, uses about 95 million tons of foundry sand per annum. The main metals cast for this industry are iron and steel. Particularly, Monosi, Sani, and Tittarelli (2010) assert that for each ton of iron or steel casting produced, about 1ton of foundry sand is employed. This quantity demonstrates that there is a profound impact of disposing of the foundry sand after use, hence the need to put the waste foundry sand into beneficial use.

2.3.3. Types of Foundry Sand

FIRST (2004) identifies two basic types of foundry sand, which are: green sand and chemically bonded sand. Green sand uses clay as the binder material. It consists of 85-95% silica, 0-2% clay, 2-10% carbonaceous additives such as sea coal, and 2-5% water. Green sand is the most commonly used moulding media by foundries. The silica sand in green sand is the bulk medium that resists high temperatures while the coating of clay binds the sand together; the water adds plasticity while the carbonaceous additives prevent the fusing of the sand into the casting surface. Chemically bonded sand on the other hand uses polymers to bind the sand grains together. It consists of 93-99% silica and 1-3% chemical binder. The silica sand is thoroughly mixed with the binder in a catalyst initiated reaction after which it cures and hardens. There are various chemical binder systems used in the foundry industry, which include phenolic-urethanes, epoxy-resins and sodium silicates (Gedik, Lav, P.Solmas, & Lav, 2008). The present study focuses on green WFS containing bentonite clay as a binder and chemically bonded WFS containing sodium silicate as a binder.

2.3.4. Characteristics of Foundry Sand

The physical and chemical characteristics of foundry sand strictly depend on type of casting process and the industry sector from which it originates as well as the type of binder systems used in the process , (Monosi et al, 2010). As earlier identified, the binder system can be clay or chemical binder systems.

a. Physical Characteristics

Foundry sand is typically sub angular to round in shape. After being used in the foundry process, a significant number of sand clusters form. This is mostly the case in green sands. When these agglomerations are broken down, the shape of individual sand grains is apparent (Bhimani et al, 2013). Table 2-1 contains the physical characteristics of WFS from a review by Siddique *et al.* (2010) on waste foundry sand and its leachate characteristics and the study by Siddique and Dhanoa (2013) on design and development of concrete using waste foundry sand as fine aggregate.

Table 2-1 Physical characteristics of waste foundry sand

Property	Rafat Siddique, Kaur, and Rajor (2010)	R. Siddique and Dhanoa (2013)
Specific gravity (g/cm^3)	2.39-2.55	2.18
Bulk relative density (Kg/m^3)	2589	-
Water absorption (%)	0.45	0.42
Clay lumps and friable particles (%)	0.1-10.1	0.8
Coefficient of permeability (cm/sec)	10.3-10.6	-
Plastic limit/Plastic index	Non plastic	Non plastic
Moisture content (%)	-	0.11
Fineness modulus	-	1.89
Material finer than 75µ (%)	-	8

From Table 2-1 it is evident that most physical properties of waste foundry sand are comparable from both results, except for the clay lumps and friable particles, where a big variation is observed in the two results. This implies that, for their study, the researchers may have used the same type of WFS.

b. Chemical Characteristics

The chemical characteristics of WFS are based on the chemical composition. In previous studies on the utilization of WFS as fine aggregate in concrete, various researchers have determined the chemical composition of WFS and their findings are as shown in Table 2-2 (Bakis, Koyuncu, & Demirbas, 2006; R. Siddique & Dhanoa, 2013; Rafat Siddique et al., 2010).

Table 2-2 Typical chemical characteristics of waste foundry sand

Constituent	Rafat Siddique et al. (2010)	Bakis et al. (2006)	R. Siddique and Dhanoa (2013)
SiO_2	87.91	96.73	83.8
Al_2O_3	4.70	0.59	0.81
Fe_2O_3	0.94	0.21	5.39
CaO	0.14	0.034	1.42
MgO	0.30	0.024	0.86
SO_3	0.09	0.01	0.21
Na_2O	0.19	0.04	0.87
K_2O	0.25	0.06	1.14
TiO_2	0.15	-	0.22
Mn_2O_3	0.02	0.01	0.047
SrO	0.03	-	-
Cl	-	0.01	-

From Table 2-2, the proportion of SiO2 is the highest though the quantities are different in all cases. Also, Siddique et al. (2010) observed a higher proportion of Aluminium than of Bakis et al. (2006) and Siddique and Dhanoa (2013). Similarly, the proportions of all the other chemical constituents vary in the respective study findings. In this light, the present study seeks to determine the specific chemical compositions and physical characteristics of both green and chemically bonded WFS and assess the impact of these characteristics on concrete quality.

2.3.5. Applications of Waste Foundry Sand

The various applications of waste foundry sand are dependent on the quantity produced within the given areas where re use is intended. Bhimani et al. (2013) reveal that the quantities of waste foundry sand produced worldwide are high, with China producing the highest. These levels of production country wise are as shown in Figure 2-1.

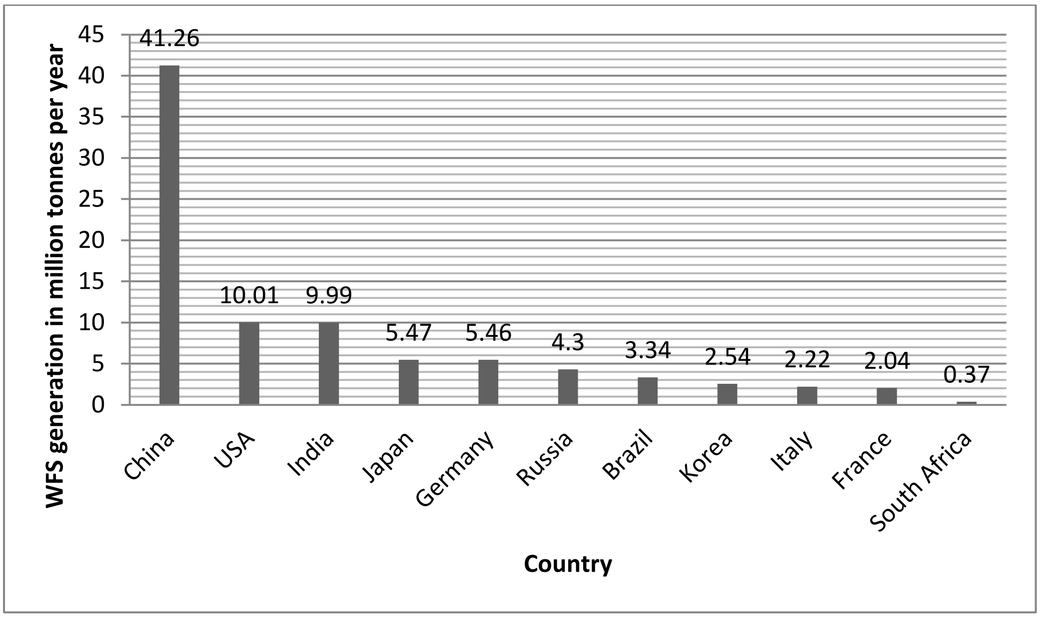

Figure 2-1 Foundry production in the world according to world casting production. Source: Bhimani et al. (2013)

One of the most important factors that determine the application of waste foundry sand is its quantity in a given location. According to FIRST (2004), the following applications of foundry sand, by ranking, based on the quantity used have been mentioned: embankments/structural fills, road base/sub base, hot mix asphalt (HMA), flowable fills, soil/horticultural, cement and concrete products as well as traction control.

In close relation to quantity, the quality of WFS is also significant. FIRST (2004) stress that the raw silica sand for making foundry sand is normally of higher quality than typical bank run or natural sands used in construction. This indicates that even after use in the moulding process, the waste sand generated from the foundries will have properties that are comparable to those of typical bank run sand for construction applications. Moreover, previous researchers have studied the use of waste foundry sand as partial replacement of fine aggregate and they assert that WFS performs satisfactorily in concrete (Amritkar, Chandak, Patil, & Jadhav, 2015; Bakis et al., 2006; Bhimani et al., 2013; Lin, C. Cheng, A. Cheng, & Chao, 2012 ; Prajapat et al., 2013; R. Siddique & Dhanoa, 2013; Rafat Siddique, Schutter, & Noumowe, 2009) .

However, other researchers maintain that waste foundry sand lowers the concrete quality when used as fine aggregate (Khatib, B. Baig, Menadi, & Kenai, 2011; Naik, Rudolph, Yoon-moon, Bruce, & Siddique, 2004; Salokhe & Desai, ND). Table 2-3 contains the compressive strength results, from the stated studies.

Table 2-3 Compressive strength (N/mm2) of concrete containing different proportions of waste foundry sand

Proportion of waste foundry sand (%)	Bhimani et al. (2013)	Salokhe and Desai (ND)		R. Siddique and Dhanoa (2013)	Amritkar et al. (2015)
		Sand from ferrous metal casting	Sand from ferrous metal casting		
0%	28.5	**31.7**	**31.7**	40	37.42
5%	-	-	-	43.3	39.14
10%	29.70	21.5	30.96	44.9	40.49
15%	-	-	-	**46.8**	**43.63**
20%	30.00	27.4	24.29	45.3	43.13
30%	**31.30**	30.96	23.85	-	-

From Table 2-3, the highlighted cells indicate the highest compressive strength obtained in the sets of specimens containing different proportions of WFS as fine aggregate in concrete. In two cases, the highest compressive strength is achieved from the control mix, implying that the use of WFS lowers the concrete quality. In three cases, the highest compressive strength is observed at 20% and 30% replacement by WFS, indicating that the use of WFS improves concrete quality. Further, the Tensile strength from the above stated studies are as shown in Table 2-4

Table 2-4 Split tensile strength (N/mm2) of concrete containing different proportions of waste foundry sand

Proportion of waste foundry sand (%)	R. Siddique and Dhanoa (2013)	Amritkar et al. (2015)
0%	4.23	2.67
5%	4.38	2.45
10%	4.57	**2.80**
15%	**4.67**	2.72
20%	4.5	2.57

From the results shown in Tables 2-4, the highlighted cells show the highest tensile strength in the specimens tested in the respective studies. From these results, it is evident that the use of WFS as fine aggregate improves the concrete quality in terms of tensile strength. In addition to the findings shown in Table 2-3 and Table 2-4, other previous studies indicate that the use of waste foundry sand as aggregate improves the resultant concrete quality in a number of cases.

Firstly, the test results of Rafat Siddique et al. (2009) indicate a marginal increase in the strength properties of plain concrete by the inclusion of used foundry sand in proportions of 10%, 20%, and 30% by weight as partial replacement of fine natural sand. Secondly, Bakis et al. (2006)identify a replacement of 10% natural sand with waste foundry sand to be the most suitable for asphalt concrete mixtures. Further, they establish that waste foundry sand does not significantly affect the environment around area where the asphalt concrete is laid, hence safe for re use. Thirdly, Lin et al. (2012)conclude that the performance of cement containing additives from waste foundry sand meets the standard requirements of cement made out of conventional materials, in terms of compressive strength, setting time as well as the degree of hydration. Further, the research findings of Bhimani et al. (2013)who investigated the water absorption of concrete cubes containing foundry sand in various proportions, indicate that the cube specimen with 50% waste foundry sand as aggregate had the lowest water absorption. Similarly, Prajapat et al. (2013) maintain that concrete containing 50% waste foundry sand as fine aggregate has the highest compressive strength and the lowest pavement thickness as well as cost of construction. In contrast to the above findings, Naik et al. (2004)establish that the partial substitution of natural sand with used foundry sand causes a small reduction in strength of concrete. Likewise, Khatib et al. (2011) explain that the incorporation of waste foundry sand in concrete causes a systematic decrease in workability and strength as well as an increase in water absorption of concrete.

Therefore, the question remains, does waste foundry sand improve or lower the quality of concrete? A highlight is given by FIRST (2004) that the quality of foundry sand depends on various aspects of foundry sand production which include the type of additives used as binders and hardeners, the amount of binder material, the type of metal cast as well as the number of times the sand is reused within the system. Consequently, the sand will differ in terms of chemical composition and physical characteristics, from foundry to foundry, which can impact its performance. They further explain that the sands produced by a single foundry are not likely to show significant variation over time and blended sands produced by a consortium of foundries often produce consistent sands.

Based on the above highlight, the present study focuses on the aspect of the a type of additive used as binder material in foundry sand, with an interest of assessing the concrete quality resulting from the separate use green and chemically bonded WFS as fine aggregate in high strength concrete.

2.4. Gap Identified from Literature

Wide research has been done on the reuse of waste foundry sand in non-foundry applications, concrete being one of them. The previous research results have shown varied performance of waste foundry sand when used as partial substitute of natural sand in concrete. In some cases a decrease in concrete quality has been observed while in other cases there is an improvement in concrete quality when waste foundry sand is used to replace natural sand in given proportions. The difference has been attributed to the variation of the characteristics of waste foundry sand based on various factors, as explained in section 2.3.5.

Notably, most of these research results do not show the specific waste foundry sand used in relation to the factors that affect the characteristics of WFS and the resultant concrete products. Furthermore, most of these studies have focused on the reuse of waste foundry sand in making low strength concrete and only a few have focused on high strength concrete. Consequently, the present study seeks to determine the characteristics of WFS based on the additive used as binder material. In relation to the WFS characteristics, it evaluates the performance of waste foundry sand in high strength concrete, which is the required concrete grade for making paver blocks.

2.5. Conceptual Framework

From the above literature review, industrial waste products may be used in concrete. Each of these waste products has unique effects on the properties of concrete. For sustainable development, if these waste products are found suitable in the construction industry, the cost of construction will be low; there will be less exploitation of virgin materials as well as a safe disposal of the waste materials. The properties of concrete containing any proportion of waste product largely depends on the characteristics of the waste product contained therein. This relationship is as shown in Figure 2-4

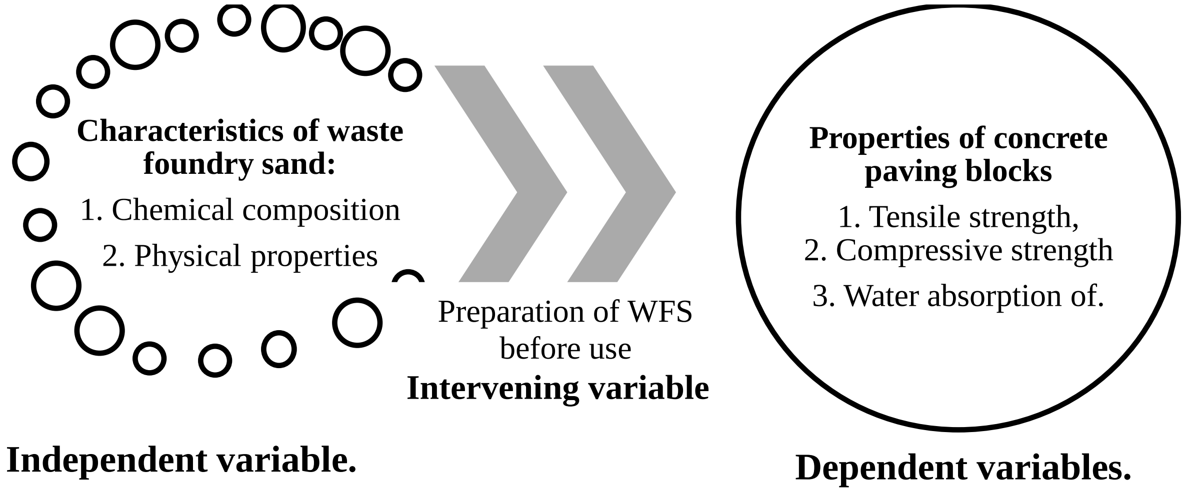

Figure 2-2 The relationship between characteristics of waste foundry sand and the properties of the resultant concrete.

From Figure 2-4, the properties of hardened concrete depend on the characteristics of the constituent materials, WFS being part. In this case, the preparation of WFS before use as fine aggregate is an intervening variable. This is because the properties of WFS sand determine the preparation required and this preparation in return influences the properties of the resultant concrete.

CHAPTER 3

Materials and Methods

3.1. Introduction

The study involved the investigation of waste foundry sand in concrete for paving blocks as fine aggregate. The main parameters studied are compressive strength, tensile strength, and water absorption of concrete paving blocks. The samples of concrete mixes containing foundry sand as partial replacement of fine aggregate were made and subjected to the appropriate tests in the laboratory.

3.2. Materials

The following materials were used in the study: firstly, store bought Cement grade 42.5, conforming to (BSEN1338 2003) for concrete pavers was used. Secondly, crushed course aggregates and natural river sand were used and their testing done as per (BS812 1995). Thirdly, the waste foundry sand used was obtained from foundry industries in Nairobi, namely East Africa Foundries Limited and Numerical Machining Complex. The sand was first sieved before use to eliminate any large metal particles. Two types of WFS, that is green and chemically bonded waste foundry sand, were collected separately from the industries. The chemical composition and physical properties of the respective WFS types, as determined in this study, are as given in Section 4.1.2 to 4.1.5. Fourthly, potable tap water was used for the concrete preparation and for curing of specimens. Lastly, a commercially available high range water reducing admixture, identified as MasterRheobuild80, was used, in quantities determined from the concrete mix design. This type of admixture helps to increase workability and flowability of the concrete mix through dispersing and deflocculating of the cement particles.

The quantities of the respective materials used were determined from the concrete mix design in Figure 3.1. As specified in BS EN 1338:2003, the quantity of admixture used in the concrete mixes was 0.3% of the calculated cement content.

Table 1 Concrete mix design form

Job title CONCRETE PAVERS

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	49 N/mm² at 28 days; Proportion defective 5 %
	1.2	Standard deviation	Fig 3	8 N/mm² or no data ... N/mm²
	1.3	Margin	C1 or Specified	(k = 1.64) 1.64 × 8 = 13.12 N/mm²; ... N/mm²
	1.4	Target mean strength	C2	49 + 13.12 = 62.12 N/mm²
	1.5	Cement strength class	Specified	(42.5)/52.5
	1.6	Aggregate type: coarse; Aggregate type: fine		(Crushed)/uncrushed; Crushed/(uncrushed)
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.38 — Use the lower value: 0.38
	1.8	*Maximum free-water/cement ratio* — Applies if the design is restricted.	*Specified*	N/A
2	2.1	Slump or Vebe time	Specified	Slump 10 – 30 mm or Vebe time 6 – 12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	190 — 190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.38 = 500 kg/m³
	3.2	*Maximum cement content*	*Specified*	N/A kg/m³
	3.3	*Minimum cement content*	*Specified*	N/A kg/m³; use 3.1 if ≤ 3.2, use 3.3 if > 3.1 — 500 kg/m³
	3.4	Modified free-water/cement ratio		N/A — 500
4	4.1	Relative density of aggregate (SSD)		2.7 known/(assumed)
	4.2	Concrete density	Fig 5	2430 kg/m³
	4.3	Total aggregate content	C4	2430 – 500 – 190 = 1740 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	36 %
	5.2	Proportion of fine aggregate	Fig 6	38 %
	5.3	Fine aggregate content	C5	38 % × 1740 = 662 kg/m³
	5.4	Coarse aggregate content	C5	1740 – 662 = 1078 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	500	190	660	1080		
per trial mix of 0.048 m³	24	9.1	32	32		

Items in *italics* are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Figure 3-1 Concrete mix design form

3.3. Determining of the physical characteristics of Aggregates

3.3.1. Gradation and Particle Size Distribution

a. Experimental Setup

This test consists of dividing up and separating aggregates through a series of test sieves, into several particle size classifications of decreasing sizes. The series of sieves were arranged in a column as shown in Plate 3-1 .

Plate 3-1 Particle size determination by sieve analysis

b. Data Collection Procedure

The mass of the particles retained on the various sieves is related to the initial mass of the material. The cumulative percentages passing each sieve are reported in numerical form. The aim of the test is to determine the particle size distribution of the aggregates and obtain grading curves for the aggregates.

The gradation and particle size distribution of the fine aggregates was done in accordance to the procedure stated in BS 812, 1995: Part 1.

c. Data Analysis and Presentation

In the study, the mass of aggregates retained in each sieve was recorded. The analysis was done by calculating the percentage of aggregates retained on each sieve and the percentage of aggregate passing through respective sieve sizes was calculated. The results obtained were presented in tables and graphs as shown in Section 4.1.2 and Appendix 1.

3.3.2. Specific Gravity and Water Absorption of Fine Aggregate

a. Experimental Setup

This test involved the determination of the bulk specific gravity and the apparent specific gravity on the basis of mass of saturated surface dry aggregate and absorption of a fine aggregate sample. The specific gravity and water absorption of the different types of aggregates were determined through the determination of sample weights in the trays before and after oven drying as well as in the pyconometer with containing water.

b. Data Collection Procedure

The test was done in accordance to the procedure stated in BS 812, 1995: Part 2 and the calculation and reporting of the results done, as explained in the standard, as follows:

$$SP = \frac{A}{(B+S-C)} \quad (3.1)$$

$$SP(SSD) = \frac{S}{(B+S-C)} \quad (3.2)$$

$$ASP = \frac{A}{B+A-C} \quad (3.3)$$

$$WA = \frac{(S-A)}{A} \times 100 \quad (3.4)$$

Where,

SP= bulk specific gravity

SP (SSD) = bulk specific gravity (Saturated Surface Dry)

ASP= apparent specific gravity

WA= water absorption

A = weight of oven dry sample

B = weight of flask and cover plate filled with water

C = weight of flask, cover, sample and water to top of flask

S = weight of saturated surface dry sample (500 g)

c. Data analysis and Presentation

The obtained data was analysed based on the Equations 3.1 to 3.4 and the results presented in Tables and graphs as shown in Section 4.1.3 and Appendix 2.

3.4. Assessing the Chemical Composition of Waste Foundry Sand

a. Experimental Setup

For each type of WFS, 100g was used to determine the chemical composition. The chemical composition of the Green and Chemically Bonded WFS was determined through X-Ray Fluorescence (XRF) spectroscopy technique. In this technique, a 100W X-ray tube was used and the system comprised of a computer controlled system developed for remote operation and monitoring of the tube and an adjustable stable 3D arrangement to procure variable excitation energies with low scattered background.

b. Data Collection Procedure

The chemical composition of the Green and Chemically Bonded WFS was determined by the respective excitations recorded from the X-Ray XRF spectroscopy and a printout showing the chemical composition was given out of the scanning machine.

c. Data Analysis and Presentation

The data obtained was expressed as percentages of the sample weight and arranged in the descending order of the quantity of the respective chemical constituents in the WFS. The quantities were then presented in tabular form.

3.5. Evaluating the Optimal Percentage Replacement of Waste Foundry Sand as Fine Aggregate in Concrete for Paving Blocks

a. Experimental Setup

The optimal proportion of WFS as fine aggregate in concrete was determined based on the performance of the paver blocks made from different mixes as shown in Table 3-2

Table 3-1: Experimental design for determining concrete properties using one-factor-at-a-time method

Property of concrete paver blocks	Age, days	Proportion of WFS, %									
		Green WFS					Chemically Bonded WFS				
		0	5	10	20	30	0	5	10	20	30
Compressive strength (MPa)	7										
	14										
	28										
Tensile strength (MPa)	7										
	14										
	28										
Water absorption (%)											

b. Data Collection Procedure

The procedures followed in casting, curing of the paver blocks as well as determining the properties of concrete pavers are as explained below.

i. Casting of Paving Blocks

The casting was done in iron moulds, with dimensions of 200x150x80mm. The procedure followed is as described in BSEN 12390, 2000 :Part 1. The moulds inside surfaces were first cleaned and oiled in order to prevent adherence of concrete to these surfaces. The moulds were then assembled and bolts and nuts tightened to prevent leakage of cement paste. The moulds were then filled with concrete in three layers, each layer being compacted using a poker vibrator to remove as much entrapped air as possible and to produce full compaction of concrete without segregation. The assembled moulds after oiling and filling with concrete mix are as shown in Plate 3-2.

(a) Assembled moulds

(b) Filled moulds

Plate 3-2 Casting of Concrete Paver blocks

ii. Curing of Specimens

Curing refers to the procedures used for promoting the hydration of cement, and consists of a control of temperature and of the moisture movement from and into the concrete. In this study, the marking and curing of the paver blocks was done according to the procedure described in BSEN12390, 2000:Part 2. Before placing specimens into a curing tank they were marked with a water proof marker with the following details: Type of mix, date of casting, duration for curing and date of crushing day. They were then placed in a curing tank at a temperature of 20^0 C ± 2^0C, some for 7 days, 14 days and for 28 days respectively.

iii. Determining the Compressive Strength of Concrete Paving Blocks

The Compressive strength test of the concrete paver blocks was done in accordance to the procedure given in BSEN12390, 2000:Part 3(E). At each testing time, block specimens were set as shown in Plate 3.3 and a load applied by switching on the machine setting it at pace rate of 15 ± 3MPa per minute. Loading was continued until no further load could be sustained by the block. The maximum load was recorded for each block and the procedure repeated for another block. The compressive strength of each block was recorded to the nearest 0.1 N/mm^2.

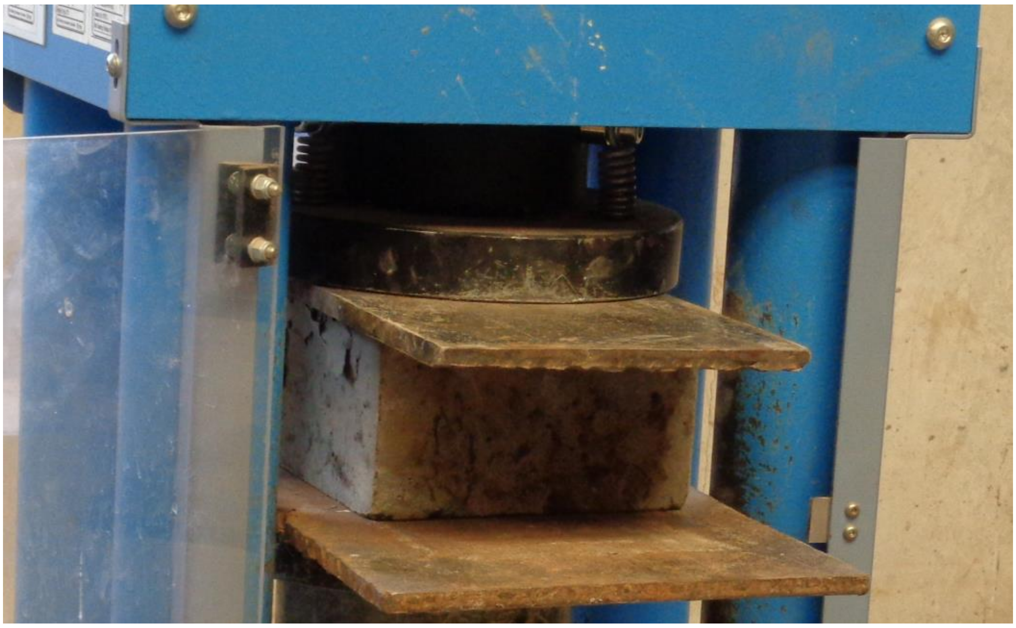

Plate 3-3 Set up for compressive strength test

iv. Determining the Tensile Strength of Paving Blocks

The procedure followed in testing the concrete paver blocks is as explained in BSEN 1338, 2003:Annex F. The block was placed in the testing machine with the packing pieces on the upper face and the bed face in contact with the bearers. The tensile strength test specimens were set as shown in Plate 3-4, where the paver block is in contact with strips on the expected splitting plane.

Plate 3-4 Set up for tensile strength test

The load was applied smoothly and progressively at a rate which corresponds to an increase in stress of (0.05 ± 0.01) MPa/s. The failure load was then recorded and the tensile strength of the blocks was calculated based on the following equations:

$S = I \times t$ (3.5)

Where,

S- is the area of the failure, in square millimetres;

l- is the mean of two measurements of the failure length, one at the top and one at the bottom

of the block, in millimetres;

t- is the thickness of the block at the failure plane in millimetres and is the mean of three

measurements; one in the middle and one at either end.

$T = 0.637 * k * \frac{P}{S}$ (3.6)

Where,

T- Is the tensile strength, in Mega Pascal

P- Is the failure load, in Newtons

k- Is a correction factor for the block thickness: k=1.00 for thickness of 80mm.

v. Determining the Water Absorption of the Concrete Paver Blocks

The water absorption of the concrete paver blocks was tested according to the procedure in BSEN1338, 2003:Annex E. The specimens were cured in potable water at a temperature of (20 ± 5) °C for 28 days, after which a constant mass M_1 was reached. Each specimen was then placed inside the oven in such a way that the distance between each specimen was at least 15 mm. The specimen was then dried at a temperature of (105 ± 5) °C for 4 days to ensure it reached constant mass M_2.

Calculation of the water absorption of each specimen as a percentage of its mass was done as follows:

$$W_a = \frac{M_1 - M_2}{M_2} \times 100\% \qquad (3.7)$$

where

W_a is water absorption

M_1 is the initial mass of the specimen (g)

M_2 is the final mass of the specimen (g).

c. Data Analysis and Presentation

After obtaining the results as explained above, the data was presented in tables and further analysed to show the various properties of WFS and separate performance of green and chemically bonded WFS. Comparisons were made by plotting graphs and drawing tables as shown in Section 4.1.5 to 4.1.8 and Appendices 3 to 5.

3.6. Cost Benefit Analysis for fine aggregates

In order to determine the economic gain of reusing WFS as fine aggregate in concrete, a cost benefit analysis was done as follows:

The components of analysis considered in the analysis include collection and landfill costs for WFS disposal as well as collection and sorting or sieving costs for WFS reuse, as identified by Denne et al. (2007). The costs of WFS landfilling disposal used in the analysis was adopted from Cointreau (2008) while the costs of purchase and collection are as incurred in the present study, as shown in Table 3-2.

Table 3-2Cost Benefit Analysis for fine aggregates

	Cost (USD/Ton)		
	Natural River Sand	**Waste Foundry Sand**	
Cost Item		**REUSE**	**DISPOSAL**
Sand Purchase	15	0	0
Collection	10	10	10
Sorting	0	5	0
Landfilling	0	0	12-20
Total cost (USD/Ton)	25	15	22-30

From Table 3-2, the cost of WFS disposal by landfilling varies depending on the land value of the landfill location. Nonetheless, it is evident that reuse of WFS as fine aggregate is cheaper than the use of natural river sand and disposal of WFS to landfills. Also, this cost of WFS disposal does not include the costs related to environmental pollution caused by WFS in the landfills.

In the given analysis, it is worth noting that the costs of landfilling and collection may vary depending on site location. Also, the cost savings derived from strength gain and other concrete property improvement achieved from WFS reuse has not been included in this analysis. Lastly, the foundry industries give the WFS for free thus zero purchase prices.

CHAPTER 4
Results and Discussion

4.1. Results

This section contains the findings of the research on separate reuse of green and chemically bonded WFS in different proportions as fine aggregate in making concrete paver blocks. Before reusing the WFS as aggregate, its chemical and physical properties were examined. In order to determine the suitability of reusing WFS, the characteristics of green and chemically bonded WFS were examined and the performance of concrete paver blocks containing 0%, 5%, 10%, 20% and 30% of both WFS types were assessed in terms of compressive strength, tensile strength and water absorption. Also, the quantity of WFS generated from the selected industrial sources of the study WFS samples is given in this section.

The strength of the concrete pavers was measured at the ages of 7, 14 and 28 days while the water absorption of the blocks was determined after 28 days of curing and subsequent 3 days of drying in the oven at 105^{0} c.

The results shown are an average of 10 replications of each test on the aggregates' physical properties and concrete paver blocks containing the respective proportions of WFS as a replacement of natural sand.

4.1.1. Waste Foundry Sand Generation from industries in Nairobi, Kenya

There are about 20 foundry industries in Kenya. Their total installed capacity is 10,000 tonnes per annum (KAM, 2016). The quantity of waste foundry sand generated from the Industries in Nairobi that were visited during the study, is as shown in Table 4-1. The WFS used as a partial replacement of fine aggregates in this study were collected from the same industries.

Table 4-1 Approximate quantity of WFS generated from selected foundry industries in Nairobi Kenya

Industry	Approximate quantity of WFS generated (tonnes per year)
East Africa Foundries Ltd	300
Numerical Machining Complex	7

According to KAM (2016) East African foundries Ltd is one of the largest foundry industries in Kenya. However, the above quantities, being from only two foundry industries, are too low compared to the annual quantities generated in other countries as identified from the previous study by Nyembwe *et al.* (2015) in Figure 2-3. Also, in order to determine the economic viability of WFS reuse in Kenya, the quantities of WFS generated countrywide have to be known.

4.1.2. Gradation and Particle Size Distribution of Fine Aggregates

The Particle size distribution of Green and chemically bonded WFS relative to natural river sand is as shown in Figure 4-1 and Table 4-2. Figure 4-1 shows the percentages of fine aggregates passing through the sieves with aperture sizes of 9.52, 4.76, 2.38, 1.68, 1.2, 0.6, 0.3 and 0.15mm.

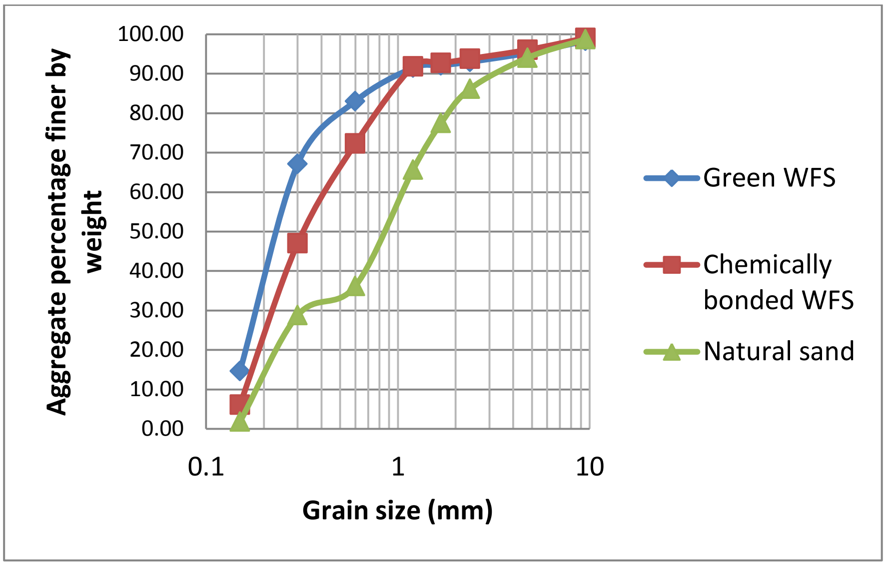

Figure 4-1 Particle size distributions of WFS and Natural river sand

From Figure 4-1 it can be seen that Natural river sand is coarser than chemically bonded WFS and the latter coarser than green WFS. The difference in particle sizes of the different sand types is also proven from the calculated fineness modulus, which are 1.75, 2.0 and 3.0 for the green WFS, chemically bonded WFS and natural river sand respectively. Based on the fineness modulus classification given by Duggal (2003), the natural river sand used in this study is classified as coarse sand which ranges from 2.9-3.2 while the green and chemically bonded WFS are finer than fine sand whose fineness modulus ranges from 2.2-2.6.

Further, based on this particle size distribution, Table 4-2 shows the aggregate percentage passing through the respective sieve aperture sizes, relative to the aggregate grading zones identified in BSEN 12620:2003. According to the grading zones, the coarsest fine aggregates are classified in Zone I while the finest fine aggregates are classified in Zone IV.

Table 4-2 Gradation of WFS and Natural river sand into various zones

Grading of WFS and Natural sand into zones according to BS EN 12620:2013							
Sieve Size in mm	Aggregate Percentage passing (%)						
	Grading Zone I	Natural river sand	Grading Zone II	Chemically bonded WFS	Grading Zone III	Green WFS	Grading Zone IV
4.75	90 - 100	96.77	90 - 100	96.04	90 – 100	95.24	95 - 100
2.36	60 - 65	90.24	75 - 100	93.78	85 – 100	93.00	95 - 100
1.2	30 - 70	72.91	55 - 90	91.87	75 -100	91.48	90 -100
0.6	15 - 34	36.23	35 - 59	72.28	60 - 79	83.04	80 - 100
0.3	5 - 20	30.14	8 - 30	47.02	12 - 40	67.09	15 - 50
0.15	0 - 10	5.90	0 - 10	6.13	0 – 10	14.62	0 -15

From Table 4-2, the natural river sand used in the present study belongs to Zone II. Secondly, the chemically bonded WFS lies in Zone III, based on the percentage of aggregates passing through the respective sieve sizes. Lastly, the green WFS belongs to grading zone IV.

From the particle size distribution of the fine aggregates shown in Figure 4-1 and Table 4-2, the proportions of each type of fine aggregates finer than 600µm are as shown in Figure 4-2.

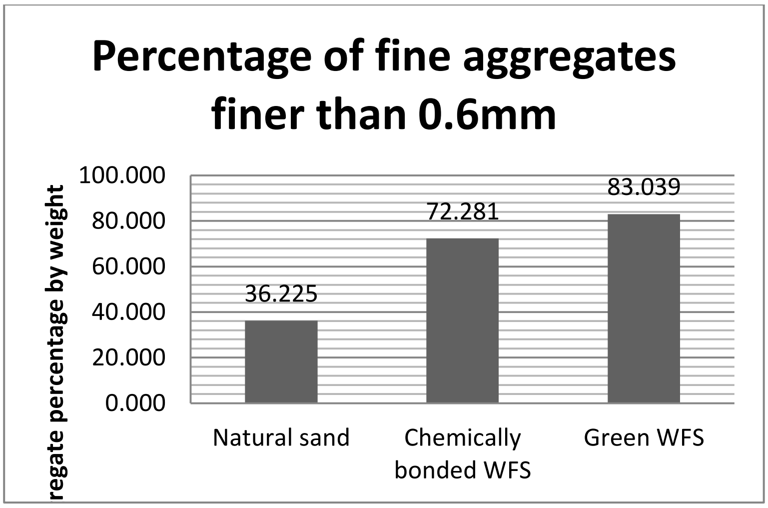

Figure 4-2 Proportion of fine aggregates finer than 600 µm

Again, Figure 4-2 shows that natural sand is the coarsest of the three while the chemically bonded WFS is coarser than green WFS. This results are closer to the findings of Siddique and Dhanoa (2013), where the percentage of WFS finer than 0.75mm is 80%. The likely implication of using WFS as aggregate in concrete is a reduction in strength. this is based on the explanation from ASTMC33 (1997) that finer aggregates provide more surface area in concrete and maximum strength in the concrete mix can only be achieved if all the surfaces of all the aggregates are covered with cement paste. This indicates that given the same quantity of cement paste, concrete containing coarser aggregates will have higher strength than concrete containing finer aggregates.

4.1.3. Void Ratio of the Waste Foundry Sand

From the determined specific gravity and bulk density of each WFS type shown in Appendix 2, the respective void ratios were determined based on the following relationship:

$$\mathrm{VR} = [1 - \frac{\mathrm{B}}{\mathrm{A}}] \qquad 4.1$$

Where

VR- Is the void ratio

B- Is the bulk density of WFS

A- Is the apparent specific gravity of WFS

The void ratio results for the green and chemically bonded WFS are as shown in Figure 4-3.

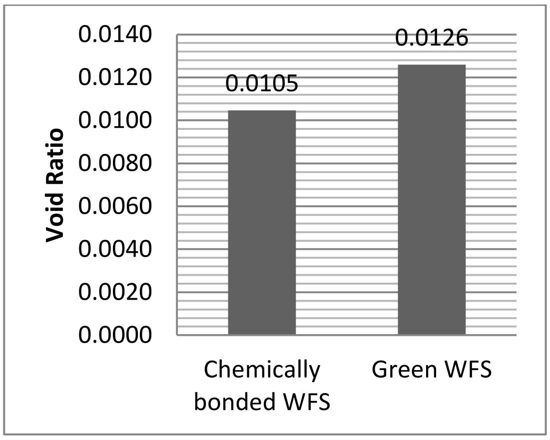

Figure 4-3 Void Ratios of WFS

From Figure 4-3, the Void ratio of green WFS is higher than that of chemically bonded WFS. Duggal (2003) explains that a higher void ratio in aggregates causes lower strength in concrete. The relationship between aggregates void ratio and concrete strength in this study is clearly highlighted in section 4.2.1.

A summary of the physical characteristics of waste foundry sand explained above is given in Table 4-3.

Table 4-3 Summary of physical properties of WFS

Physical property	Green WFS	Chemically Bonded WFS
Material finer than 0.6mm	83	72
Fineness Modulus	1.75	2.01
Bulk Relative density (Kg/m3)	2330	2560
Water Absorption (%)	0.54	0.41
Void Ratio	0.0126	0.0105

4.1.4. Chemical composition of Waste Foundry Sand

The chemical composition of both Green and Chemically Bonded WFS is as shown in Table 4-4. In the Table, the highlighted cells show the chemical composition of WFS from previous studies.

Table 4-4 Chemical composition of WFS

Component	Proportion (%) from present study		Proportion (%) from previous studies		
	Green WFS	Chemically Bonded WFS	Siddique (2010)	Bakis and Koyuncu (2006)	Siddique and Dhanoa (2013)
Silica as SiO_2	64.472	93.912	87.91	96.83	83.8
Calcium as CaO	10.383	0.741	0.14	0.034	1.42
Aluminium as Al_2O_3	9.961	2.283	4.7	0.59	0.81
Magnesium as MgO	6.333	1.241	0.3	0.024	0.86
Iron as Fe_2O_3	5.165	0.419	0.94	0.21	5.39
Potassium as K_2O	1.511	0.395	0.25	0.06	1.14
Sulphur as SO_3	0.75	0.08			
Titanium as TiO_2	0.581	0.198	0.15		0.22
Chlorine as Cl	0.268	0.005		0.01	
Phosphorous as P_2O_5	0.263	0.113			
Manganese as Mn_2O_3	0.093	0.017	0.02	0.01	0.047
Copper as Cu	0.072	0.004			
Zinc as Zn	0.049	0.007			

From Table 4-3, the proportion of Silica is lower in Green WFS than it is in Chemically Bonded WFS. In contrast, the proportions of all the other constituents are higher in Green WFS than in Chemically Bonded WFS. Also, despite the fact that the previous researchers: (Bakis et al., 2006; R. Siddique & Dhanoa, 2013; Rafat Siddique et al., 2010) did not state the type of WFS whose chemical composition is shown in the highlighted cells of Table 4-3, it is evident that the proportions of the various WFS constituents are closer to those of chemically bonded WFS observed in the present study. This is because, as described earlier in section 2.3.3, WFS is either green or chemically bonded, depending on the type of additive used as the binder material.

4.1.5. Tensile Strength of Concrete Paver Blocks

This section contains the results of tensile strength of concrete paver blocks containing green and chemically bonded WFS respectively.

The tensile strength of concrete paver blocks made using different proportions of green WFS is shown in Figure 4-4. The strength was tested at the ages of 7, 14 and 28 days.

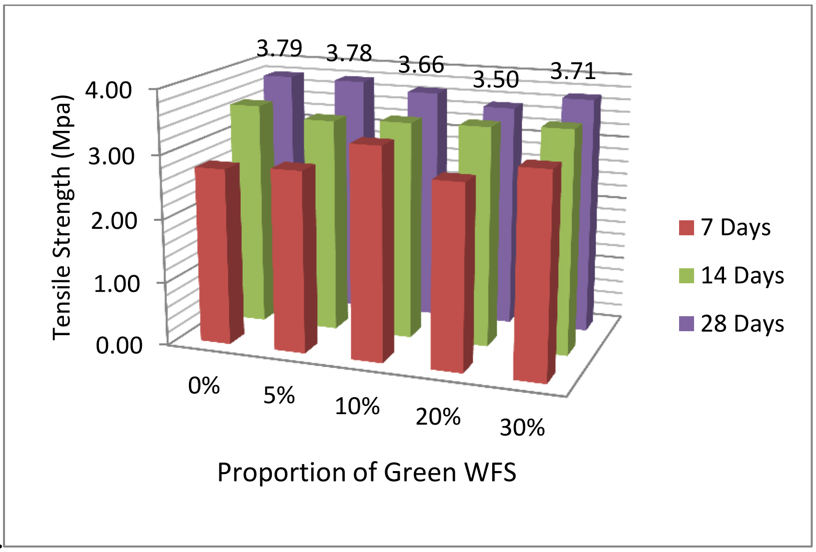

Figure 4-4 Tensile strength of concrete paver blocks containing Green WFS

From Figure 4-4, it can be observed that the tensile strength of the paver blocks increases with age, from 7 days to 28 days in all the proportions of green WFS replacement. Also, at the age of 28 days, the tensile strength of the blocks containing green WFS is comparable to that of the blocks containing only natural sand as a fine aggregate. Further, the 28 days tensile strength values of the paver blocks are as shown by the data labels in Figure 4-4 , at different proportions of green WFS replacement. From the values, it is notable that the tensile strength at 0% green WFS replacement is the highest, being 3.79MPa at 28 days. This is nearly equal to the 28 days tensile strength of 3.78MPa achieved at 5% green WFS replacement, which is the highest among the concrete paver blocks containing green WFS. This trend differs from that observed by Amritkar *et al.* (2015), where the concrete specimens from the control mix had lower tensile strength than the specimens containing 10% and 15% WFS as fine aggregate. Also, it is notable that at the ages of 7, 14 and 28 days, the tensile strength of the blocks increases with increase in WFS replacement from 20% to 30%. This is different from the decrease in strength observed when the WFS replacement increases from 10% to 20%. The latter trend can be attributed to the increase in surface area, with increase in WFS, which results to lack of proper coating of all aggregate surfaces with cement paste thus lowering the bond strength between the aggregates. In relation to the standard 3.6 MPa tensile strength required in BS EN 1338:2003, the required quality in terms of tensile strength at the age of 28 days is achieved at 0%, 5%, 10% and 30% of green WFS as fine aggregate.

Also, for the concrete paver blocks containing chemically bonded WFS, the tensile strength at different percentage replacements and ages is as shown in Figure 4-5.

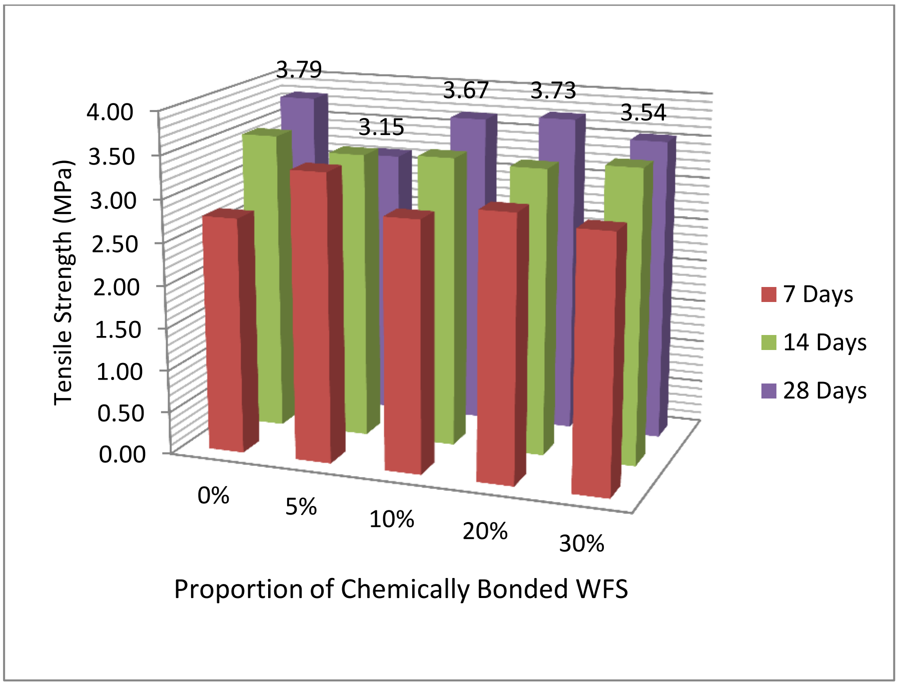

Figure 4-5 Tensile strength of concrete paver blocks containing Chemically Bonded WFS

From Figure 4-5, the tensile strength of paver blocks increases with age at various proportions of chemically bonded WFS replacement. On the contrary, in blocks containing 5% chemically bonded WFS, the 28 days tensile strength is lower than 14 days tensile strength. Further, the strength is highest in blocks with 0% chemically bonded WFS, at 3.79 MPa. Even so, this is close to the tensile strength of 3.73MPa achieved in blocks containing 20% chemically bonded WFS, which is the highest in the blocks containing chemically bonded WFS. This observed trend differs from the previous study findings where the tensile strength of concrete specimens was highest at 15% WFS inclusion as fine aggregate and lowest in specimens of the control mix (Siddique and Dhanoa 2013).

In relation to the standard required in BS EN 1338:2003, the required quality in terms of tensile strength at the age of 28 days is achieved at 0%, 10% and 20% of Chemically Bonded WFS as fine aggregate.

4.1.6. Compressive Strength of Concrete Paver Blocks

On a similar note as, this section contains the results of compressive strength of concrete paver blocks containing green and chemically bonded WFS respectively.

The compressive strength of concrete paver blocks made using different proportions of green WFS is shown in Figures 4-6. The strength was tested at the ages of 7, 14 and 28 days.

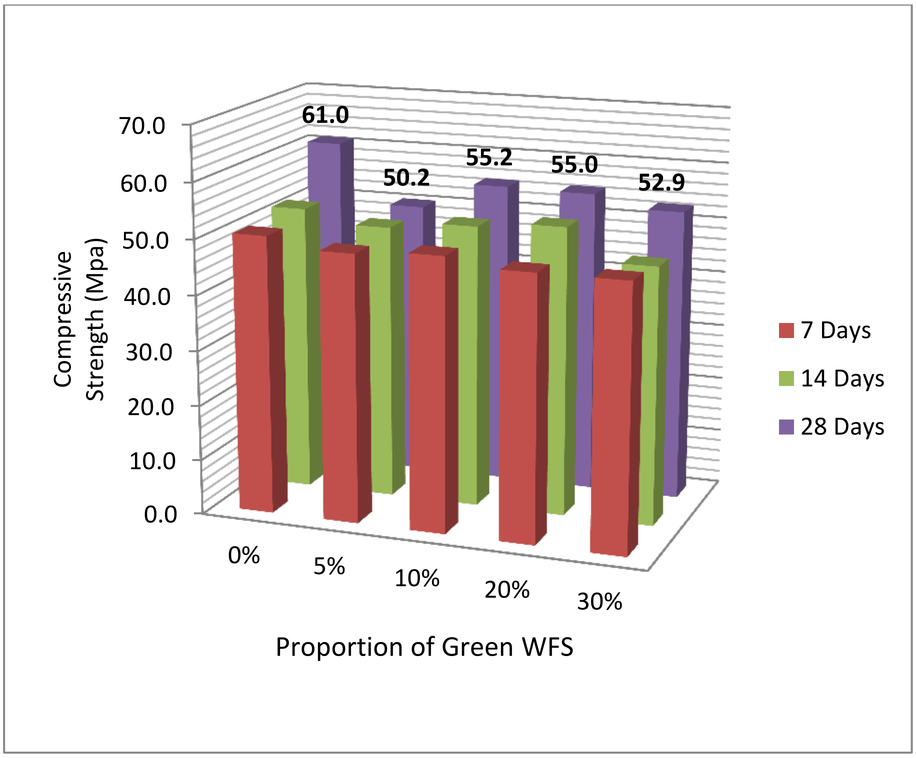

Figure 4-6 Compressive strength of concrete paver blocks containing Green WFS

Parallel to the trend observed with tensile strength, Figure 4-6 shows that the compressive strength of blocks increases with age, from 7 days to 28 days, at different proportions of green WFS replacement. Further, the compressive strength of concrete paver blocks containing only natural sand as fine aggregate is the highest at 61MPa. Close to this compressive strength of the blocks made of conventional fine aggregates is 55.2 MPa, achieved in the paver blocks containing 10% green WFS. This trend is comparable to the previous study findings that showed the highest concrete compressive strength of 31.7MPa in specimens from the control mix and followed closely by 30.96MPa of specimens containing 10% WFS (Salokhe and Desai ND). In relation to the standard required in ASTM 1988, it is evident that the quality of the paver blocks made from all the proportions 0%, 5%, 10%, 20% and 30% of green WFS as a fine aggregate meets the recommended compressive strength of 50MPa at the age of 28 days.

On the same note, the compressive strength of concrete paver blocks containing chemically bonded WFS, at different percentage replacements and ages is as shown in Figure 4-7.

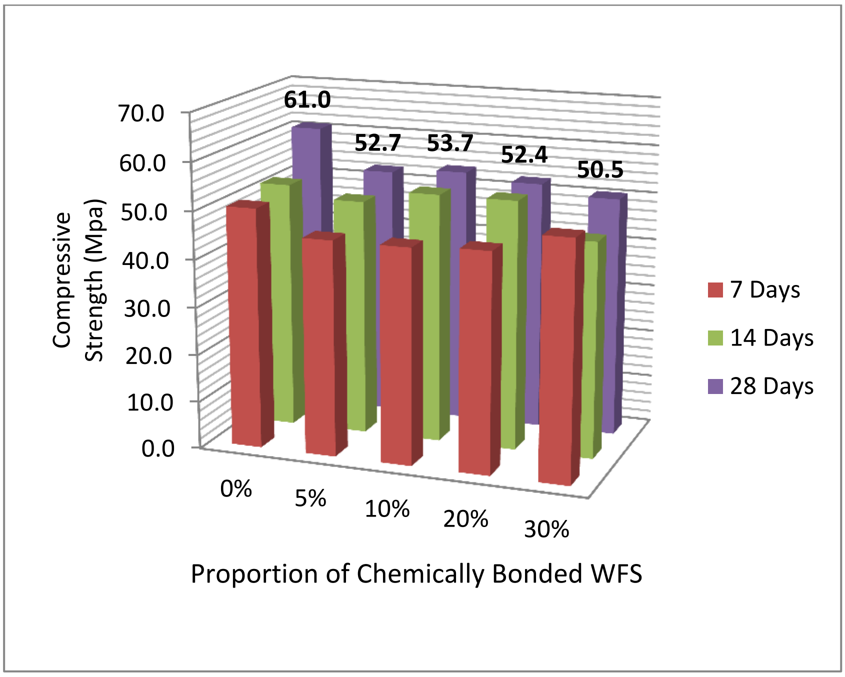

Figure 4-7 Compressive strength of concrete paver blocks containing Chemically Bonded WFS

From Figure 4-7, the compressive strength of the paver blocks increases with age at various proportions of Chemically Bonded WFS, except those blocks with 30% Chemically Bonded WFS, where the compressive strength at 14 days is found to be lower than that at 7 days. Also, the 28 days compressive strength of concrete paver blocks containing only natural sand as fine aggregate is the highest at 61MPa. Close to this compressive strength of the blocks made of conventional fine aggregates is 53.7 MPa, attained in the paver blocks containing 10% Chemically Bonded WFS as fine aggregate. In relation to the standard required in ASTM 1988, it is plain that the quality of the paver blocks made from all the proportions 0%, 5%, 10%, 20% and 30% of chemically bonded WFS as a fine aggregate meets the recommended compressive strength of 50MPa in ASTM 1988.

4.1.7. Water Absorption of Concrete Paver Blocks

The water absorption as percentage of mass of the concrete paver blocks is explained in this section for the respective types of WFS used. The wet weight of the blocks was taken after 28 days of curing and the dry weight in the subsequent 4 days of oven drying. The water absorption of concrete paver blocks made using different proportions of green WFS is shown in Figure 4-8.

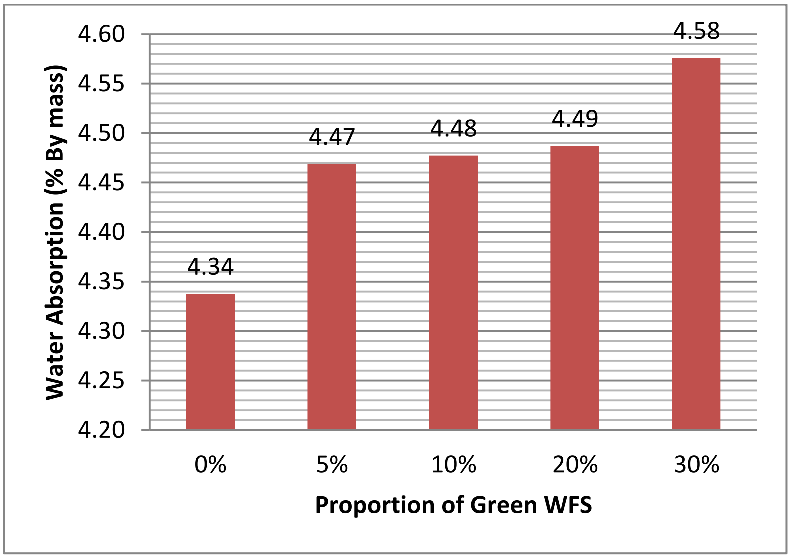

Figure 4-8 Water absorption of paver blocks containing Green WFS

From Figure 4-8, it is clear that the concrete paver blocks containing 0% green WFS have the lowest water absorption while the blocks containing 30% green WFS have the highest water absorption. The increase in water absorption of the concrete blocks with increasing amount of WFS is attributed to the fineness of WFS, which causes an increase in the surface of hydration products, thus increasing water absorption (Prabhu *et al* 2015). The water absorption of the blocks ranges from 4.3 to 4.6% by mass. Nonetheless, the quality of paver blocks in all proportions of green WFS attains the standard water absorption value of ≤6% by mass recommended in BS EN 1338:2003.

Likewise, water absorption of concrete paver blocks made using different proportions of Chemically Bonded WFS is shown in Figure 4-9.

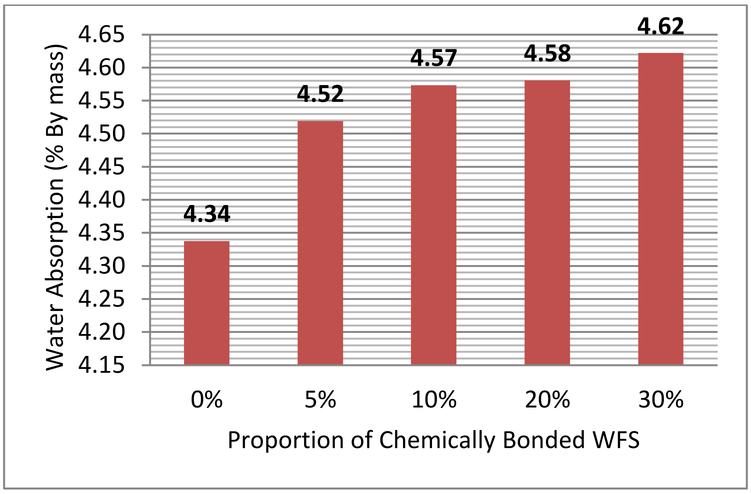

Figure 4-9 Water absorption of paver blocks containing Chemically Bonded WFS

From Figure 4-9, the concrete paver blocks containing 0% chemically bonded WFS have the lowest water absorption and highest at 30% replacement, a trend which is similar to that observed when green WFS is used. Again, the increase in water absorption of the concrete blocks with increasing amount of WFS is attributed to the fineness of WFS, which causes an increase in the surface of hydration products, thus increasing water absorption (Prabhu *et al* 2015). Despite these variances, the water absorption ranges from 4.3 to 4.6% by mass. Also, from these values, the quality of paver blocks in all proportions of chemically bonded WFS attains the standard water absorption value of ≤6% by mass recommended in BS EN 1338:2003.

The trend from the results of water absorption of concrete paver blocks observed in this study differs from that of previous study findings where the concrete from the control mix had the highest water absorption at 1.91% by mass while the concrete specimens containing 20% WFS as fine aggregate had the lowest water absorption at 1.13% by mass (Salokhe and Desai ND).

4.1.8. Optimal Proportion of WFS as Fine Aggregate

In trying to examine the performance of WFS as fine aggregate in concrete for paver blocks, we have shown the compressive strength, tensile strength and water absorption of paver blocks containing the two different types of WFS, that is green WFS and chemically bonded WFS. Whereas the water absorption of the paver blocks was within the range of 4.3 to 4.6% by mass in both green and chemically bonded WFS, the optimal values of tensile and compressive strength at 28 days differed in the two types of WFS as shown in Table 4-11.

Table 4-5 Optimal values for 28days compressive and tensile strength

	Highest 28 Days Strength (MPa)		Lowest Water absorption (% By mass)
WFS Type	**Tensile Strength**	**Compressive Strength**	
1. Green	3.78Mpa at 5% WFS	55.2Mpa at 10% WFS	4.47 at 5% WFS
2. Chemically Bonded	3.73Mpa at20% WFS	53.7MPa at 10% WFS	4.52 at 5% WFS
	Optimal WFS replacement and respective Concrete properties		
WFS Type	**28 days Tensile Strength (MPa)**	**28 days Compressive Strength (MPa)**	**Water absorption (% By mass)**
1. Green	3.66Mpa at 10% WFS	55.2Mpa at 10% WFS	4.48 at 10% WFS
2. Chemically Bonded	3.67Mpa at10% WFS	53.7MPa at 10% WFS	4.57 at 10% WFS

From Table 4-10, it is evident that the highest tensile and compressive strength are both higher when Green WFS is used than when Chemically Bonded WFS is used. In addition, the observed concrete water absorption is lower when green WFS is used than when chemically bonded WFS is used as fine aggregate. Lastly, from the economic and environmental point of view, the optimum replacement of green and chemically bonded WFS is 10%. This is because; at 10% the quality of paver blocks meets the required standard in terms of tensile strength, compressive strength and water absorption. At the same time, it helps in reducing the negative economic and environmental impacts of obtaining natural river sand and disposal of WFS.

4.2. Discussion

In this section, the relationship between characteristics of fine aggregates and properties of hardened concrete paver blocks will be explained. Also, the observed trends of paver block strength development with time will be expounded.

4.2.1. Impact of Aggregates' Physical Characteristics on Strength of Concrete Paver Blocks

As shown in Table 4-2 and Figure 4-2, the natural sand used is coarser than both Chemically Bonded WFS and Green WFS. Consequently, the compressive and tensile strength is highest in the blocks made from the control mix that contained only natural sand as fine aggregate, compared to those containing green and chemically bonded WFS as shown in Figure 4-4 to Figure 4-7. These findings concur with those of (Siddique and Dhanoa 2013, Rashid *et al.* 2014) who establish that strength of concrete decreases with increase in fineness of aggregates. On the same note, ASTMC33 (1997) establishes that finer aggregates provide more surface area in concrete and maximum strength in the concrete mix can only be achieved if all the surfaces of all the aggregates are covered with cement paste. This indicates that given the same quantity of cement paste, concrete containing coarser aggregates will have higher strength than concrete containing finer aggregates.

Despite this clear relation between aggregate particle size and concrete strength, a different trend is observed from Table 4-11 where Green WFS, which finer thus in Zone IV, produces paver blocks of higher strength than Chemically Bonded WFS, which is in Zone III as shown in Table 4-2. This contrast can be attributed to the difference in chemical composition of the green and chemically bonded WFS, as will be explained later in this section.

Another physical aspect of aggregates that affects concrete strength is the void ratio. Figure 4-3 shows that the void ratio of green WFS is higher than the void ratio of chemically bonded WFS. ASTMC33 (1997) explains that a higher void ratio of aggregates would be a cause of lower strength in concrete because all voids in the concrete mix have to be filled with cement paste in order to achieve maximum strength. However, from the findings of the present study, green WFS has a higher void ratio but it is found to produce concrete paver blocks of higher strength than chemically bonded WFS. Again, this contrast can be attributed to the different chemical compositions of the two types of WFS.

4.2.2. Impact of Chemical Composition of WFS on Strength of Concrete Paver Blocks

Having deliberated the impacts of the physical characteristics of aggregates, the effect of their chemical composition on concrete strength needs to be considered. From Table 4-3, the following can be deduced: the proportion of silica in green WFS is 0.7 times that in chemically bonded WFS. Based on the previous study findings, the expected result of having higher silica content in a concrete mix is higher strength (Bhanja and Sengupta 2005, Cakır and Sofyanlı 2015). In contrast, the present study results show that the concrete paver blocks containing chemically bonded WFS have lower strength than those containing green WFS despite the high silica content in the former.

This suggests that the impact of the other chemical constituents in the two types of WFS also have a considerable impact on the strength of concrete. Firstly, the proportions of all the other chemical constituents shown in Table 4-3 are higher in green WFS that in chemically bonded WFS. Particularly, the amounts of calcium, aluminium, magnesium, iron, potassium, sulphur, titanium, chloride, phosphorous, manganese, copper and zinc are higher in green WFS by factors of 14, 4.4, 5.1, 12.3, 2.8, 9.4, 2.9, 53.6, 2.3, 5.5, 18.0 and 7.0 respectively. Previously, studies have been done to determine the separate effects of calcium, aluminium, magnesium, iron, potassium, sulphur, titanium, chloride, phosphorous, manganese, copper and zinc on the strength properties of concrete (Abalaka and Babalaga 2011, Venkateswara *et al.* 2011, Chavan and Kulkarni 2013, Hassan *et al.* 2013, Alzaed 2014, Ramesh 2014, Manoj Kumaar *et al.* 2015, Odeyemi *et al.* 2015). These previous research findings indicate that the presence of higher contents of the above chemical constituents in concrete results to increase compressive and tensile strengths of concrete. Based on these previous study findings, the present study results also reveal that the combined effect of the presence of higher proportions of calcium, aluminium, magnesium, iron, potassium, sulphur, titanium, chloride, phosphorous, manganese, copper and zinc are higher in green WFS are the reason for higher strength of concrete paver blocks containing green WFS. This is despite the finer particle size, higher void ratio and lower silica content in green WFS.

4.2.3. Strength Development of the Concrete Paver Blocks with Age

Regarding the aspect of concrete strength development with age, in few cases of section 4.1, an unexpected trend was observed. Whereas it is expected that the strength of concrete increases with time, the 28 days tensile strength of paver blocks containing 5% chemically bonded WFS was found to be lower than the same strength at 14 days. This is a decrease in strength with age. Similarly, the 14 days compressive strength of paver blocks containing 30% chemically bonded WFS was lower than the same strength at 7 days. The possible causes of this decrease in strength with age are air entrapment in concrete during compaction of the particular paver blocks and higher temperature during strength development, which would cause faster hydration reaction but lower final strength due to a poorly structured and more porous hardened cement paste (The constructor 2016).

CHAPTER 5

Conclusions and Recommendations

5.1. Conclusion

This study mainly focuses on the determination of the chemical composition of waste foundry sand generated from selected foundry industries in Nairobi, assessment of the physical properties of the waste foundry sand and determination of the optimum percentage replacement of waste foundry sand as fine aggregate in concrete for paving blocks. The performance of Waste Foundry Sand as fine aggregate in concrete for paver blocks was assessed in terms of compressive strength, tensile strength and water absorption. The following are the conclusions based on the experimental results obtained.

1. The chemical composition of green and chemically bonded WFS is different. Particularly, the proportion of silica in green WFS is lower at a factor of 0.7 times that in chemically bonded WFS while the proportions of calcium, aluminium, magnesium, iron, potassium, sulphur, titanium, chloride, phosphorous, manganese, copper and zinc are higher in green WFS by factors of 14, 4.4, 5.1, 12.3, 2.8, 9.4, 2.9, 53.6, 2.3, 5.5, 18.0 and 7.0 respectively.
2. The physical properties of green and chemically bonded WFS vary. Green WFS is finer than chemically bonded WFS but both types of WFS are finer than natural river sand. Also, green WFS has a higher void ratio than chemically bonded WFS. The use of only natural sand as fine aggregate in concrete produces higher strength compared to the separate use of green and chemically bonded WFS at different proportions. This is attributed to the coarser particles in natural sand than in both WFS types.

   Despite its finer particles, higher void ratio and lower silica content, the use of green WFS as fine aggregate achieves higher concrete strength than the use of chemically bonded WFS due to the higher proportion of calcium, aluminium, magnesium, iron, potassium, sulphur, titanium, chloride, phosphorous, manganese, copper and zinc contained in the former.

3. From the strength and water absorption results, the optimum replacement of green and chemically bonded WFS as fine aggregate is 10%. Nonetheless, the use of WFS as fine aggregate in concrete can produce paver blocks of the quality required in BS 1338:2003 and ASTM 1988 standards, that is 3.6MPa tensile strength, ≤6% by mass water absorption and 50MPa compressive strength at 28 days.

5.2. Recommendations

Based on the findings of the present study, previous studies and the resultant conclusions, the following recommendations are made.

1. The reuse of green or chemically bonded waste foundry sand as fine aggregate for high strength concrete such as making of concrete paver blocks is recommended.
2. The recommended proportion is 10% green and chemically bonded WFS.

5.3. Areas for Further Study

1. A further study is recommended to assess the performance of the specific types of waste foundry sand as fine aggregate at closer % replacements within the optimum range observed from the present study.
2. A related study is recommended to investigate the effect of combining green and chemically bonded WFS as fine aggregate on the properties of concrete.
3. We recommend a further study to determine the quantity of WFS generated from foundries in Kenya per year.

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Appendices

Appendix 1: Particle Size Distribution of Fine Aggregates from Sieve Analysis

Appendix 1.1: Particle Size Distribution of Natural River Sand

Natural River Sand												
Sieve size ,mm	**Aggregate weight retained (g)**										**Average aggregate weight retained (g)**	**Stdev**
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P8**	**P10**		
9.52	4	20.5	13	6.5	4	6.5	16.5	34.5	4.5	20.5	12.50	9.52
4.76	50	48.5	46	48.5	50	49	50.5	48	50.5	48.5	46.70	1.48
2.38	77.5	78.5	78.5	79.5	77.5	80	80.5	79	81	78.5	78.50	1.14
1.68	90.5	87.5	91.5	91	90.5	89	86.5	85.5	83.5	87.5	86.70	2.56
1.2	114.5	118	116	116.5	114.5	117	114	118.5	120.5	118	117.40	1.98
0.6	269	271	263.5	275	269	269	269	264	271	271	288.20	6.58
0.3	71	77	84.5	85.5	71	68	62	58	60	77	77.60	9.37
0.15	282	278.5	290	282	282	280	293	290.5	295	278.5	263.90	8.75
Pan	19	17.5	14	15	19	23	24.5	21	11.5	17.5	23.60	4.15
Total	997.5	997	997	999.5	997.5	978	997	999	998.5	997	995.00	6.00

Appendix 1.2: Particle Size Distribution of Chemically Bonded WFS

CHEMICALLY BONDED WFS												
Sieve size ,mm	Aggregate weight retained (g)										Average aggregate weight retained (g)	Stdev
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P8**	**P10**		
9.52	3	8	7.5	8.5	3	7	5.5	10	7.5	7	6.67	2.15
4.76	29.5	31.5	31.5	33	29.5	30	25.5	32.5	21	30	29.33	3.43
2.38	23.5	22.5	23	23	23.5	21	19	24	23	21	22.50	1.47
1.68	11.5	10.5	10	11	11.5	11	11	11	12	11	11.06	0.52
1.2	9.5	5.5	9.5	9	9.5	9.5	4.5	6.5	4.5	9.5	7.56	2.11
0.6	130	131	137.5	138.5	131	134.5	162.5	130	144	134.5	137.67	9.40
0.3	166	183.5	187	170	169	182	172.5	190	184	185	178.22	8.17
0.15	527	513.5	508	515	523	505.5	529.5	510	517	512	516.50	7.66
Pan	80.5	89	83.5	89	80.5	87	64.5	83	84	87	82.33	6.78
Total	997	995	997.5	997	997	996	994.5	998	997	996	996.56	1.05

Appendix 1.3: Particle Size Distribution of Green WFS

GREEN WFS												
Sieve size ,mm	**Aggregate weight retained (g)**										**Average aggregate weight retained (g)**	**Stdev**
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P8**	**P10**		
9.52	12	9.5	11	9.5	21	26.5	13.5	8	18.5	21	14.39	5.95
4.76	28	29.6	27	29	34.5	33.5	33.5	27	28.5	31.5	30.07	2.68
2.38	24	24	21.5	26	22	25.5	25.5	26.5	27.5	22	24.72	1.98
1.68	9.5	9	8	9.5	9	10.5	10.5	11	11	9	9.78	0.95
1.2	5	3	3	4	3.5	11	11.5	12	12.5	3.5	7.28	4.01
0.6	87	88	97.5	94.5	95	92	83	86.5	89.5	88.5	90.33	4.27
0.3	181	201.3	205.5	202	193	150.5	152	174	170	193	181.03	19.15
0.15	520	519	504	495	496	504	517.5	516	512	500.5	509.28	9.14
Pan	128	112	121	126	124	143.5	130	136	129	127	127.72	7.96
Total	994.5	995.4	998.5	995.5	998	997	977	997	998.5	996	994.60	6.05

Appendix 2: Specific Gravity and Absorption of Fine Aggregates

Appendix 2.1: Specific Gravity and Water Absorption of Chemically Bonded WFS

Chemically Bonded WFS												
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**Average**	**Stdev**
Bulk specific gravity	2.57	2.57	2.53	2.59	2.46	2.53	2.57	2.57	2.54	2.54	2.55	0.04
Bulk specific gravity (Saturated surface dry)	2.58	2.58	2.54	2.60	2.48	2.54	2.58	2.58	2.55	2.55	2.56	0.04
Apparent specific gravity	2.61	2.59	2.55	2.62	2.50	2.55	2.59	2.59	2.57	2.57	2.57	0.04
Absorption (%)	0.70	0.20	0.40	0.40	0.60	0.40	0.40	0.20	0.40	0.40	0.41	0.15

Appendix 2.2: Specific Gravity and Water Absorption of Green WFS

Green WFS												
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**Average**	**Stdev**
Bulk specific gravity	2.22	2.33	2.33	2.33	2.32	2.33	2.29	2.33	2.33	2.35	2.31	0.04
Bulk specific gravity (Saturated surface dry)	2.24	2.35	2.37	2.35	2.32	2.34	2.29	2.33	2.33	2.36	2.33	0.04
Apparent specific gravity	2.26	2.39	2.42	2.37	2.32	2.35	2.29	2.33	2.33	2.38	2.34	0.05
Absorption (%)	0.70	1.21	1.63	0.81	0.00	0.40	0.00	0.00	0.00	0.60	0.54	0.57

Appendix 3: Tensile Strength of Concrete Paver Blocks

Appendix 3.1: 7 Days Tensile Strength

	7 DAYS TENSILE STRENGTH (MPa)											
Proportion of WFS	Green WFS											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Average**	**Stdev**
0%	2.59	3.01	3.94	2.47	2.42	2.42	1.85	3.01	2.78	3.22	2.77	0.57
5%	2.96	3.07	2.52	3	1.92	2.68	2.62	3.42	3.45	2.83	2.85	0.45
10%	2.59	3.21	3.33	4.35	2.33	3.06	4.12	3.53	3.71	2.92	3.32	0.64
20%	3.9	1.67	2.3	3.1	2.39	2.31	3.54	3.26	3.82	2.51	2.88	0.75
30%	3.4	3.71	2.9	4.34	2.7	2.94	3.23	2.93	2.7	2.8	3.17	0.52
Proportion of WFS	Chemically Bonded WFS											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Average**	**Stdev**
0%	2.59	3.01	3.94	2.47	2.42	2.42	1.85	3.01	2.78	3.22	2.77	0.57
5%	2.86	2.64	3.47	3.68	4.07	3.89	4.13	2.81	3.41	2.84	3.38	0.56
10%	3.29	2.99	3.19	3.65	3.16	2.67	2.7	2.18	2.92	2.6	2.94	0.42
20%	3.97	3.29	3.83	1.38	2.71	3.93	3.03	2.54	2.97	3.3	3.10	0.78
30%	3.49	2.51	3.21	2.87	3.42	2.52	3.48	2	3.12	3.14	2.98	0.50

Appendix 3.2: 14 Days Tensile Strength

	14 DAYS TENSILE STRENGTH (MPa)											
Proportion of WFS	Green WFS											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Average**	**Stdev**
0%	3.54	3.52	3.49	3.54	3.52	3.43	3.58	3.55	3.46	3.56	3.52	0.05
5%	3.24	2.96	3.08	4.01	2.67	2.76	4.03	4.07	3.35	3.44	3.36	0.52
10%	2.99	2.73	4.1	2.74	3.55	3.85	3.7	3.68	3.36	3.47	3.42	0.46
20%	2.82	3.17	3.56	3.55	4.19	3.42	3.76	3.98	2.95	2.99	3.44	0.46
30%	2.79	3.35	4.21	3.15	3.11	3.46	3.84	3.75	3.48	3.79	3.49	0.42
Proportion of WFS	Chemically Bonded WFS											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Average**	**Stdev**
0%	3.54	3.52	3.49	3.54	3.52	3.43	3.58	3.55	3.46	3.56	3.52	0.05
5%	3.24	3.41	3.39	3.21	2.54	2.61	3.92	3.93	3.73	3.71	3.37	0.49
10%	2.92	3.72	3.47	2.92	3.27	2.59	3.72	3.78	3.52	4.15	3.41	0.48
20%	3.17	1.81	3.12	3.22	3.81	3.43	3.54	3.86	3.97	3.67	3.36	0.62
30%	2.8	2.81	3.11	3.07	3.74	3.46	4.72	3.93	3.57	3.25	3.45	0.58

Appendix 3.3: 28 Days Tensile Strength

	28 DAYS TENSILE STRENGTH (MPa)											
Proportion of WFS	Green WFS											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Average**	**Stdev**
0%	3.82	4.74	3.58	3.19	3	2.89	5.26	4.44	3.22	3.75	3.79	0.79
5%	3.88	3.66	3.6	3.98	4.4	3.96	3.63	3.92	3.44	3.31	3.78	0.31
10%	3.67	4.7	3.7	3.72	3.8	4.97	2.59	2.75	3.46	3.29	3.67	0.74
20%	3.77	3.89	2.83	4.09	2.86	2.88	3.15	3.36	4.5	3.7	3.50	0.58
30%	3.76	3.8	3.19	3.53	3.86	3.71	3.93	3.78	3.83	3.73	3.71	0.21
Proportion of WFS	Chemically Bonded WFS											
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**Average**	**Stdev**
0%	3.82	4.74	3.58	3.19	3	2.89	5.26	4.44	3.22	3.75	3.79	0.79
5%	3.76	3.69	2.81	3.04	2.71	2.75	3.36	3.47	3.10	2.83	3.15	0.39
10%	3.75	4.38	2.67	2.42	3.76	4.28	3.87	3.69	3.12	4.72	3.67	0.74
20%	3.98	3.75	3.39	3.22	3.85	3.75	3.7	4.23	3.65	3.78	3.73	0.28
30%	4.07	3.58	2.98	3.6	4.15	3.56	3.52	3.35	3.21	3.37	3.54	0.36

Appendix 4: Compressive Strength of Concrete Paver Blocks

Appendix 4.1: 7 Days Compressive Strength

	7 DAYS COMPRESSIVE STRENGTH (MPa)											
Proportion of WFS	Green WFS											
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**Average**	**Stdev**
0%	45.53	49.2	54.51	58.25	49.13	49.32	50.26	56.75	48.86	42.93	50.47	4.77
5%	46.71	56.78	45.49	58.67	58.55	45.08	47.88	51.93	37.64	37.52	48.63	7.80
10%	55.67	57.72	49.32	53.57	55.65	56.23	48.11	47.88	34.66	36.6	49.54	8.14
20%	55.55	50.55	52.72	50.17	50.04	44.57	47.57	54.69	45.33	42.97	49.42	4.27
30%	52.38	51.04	53.15	47.62	51.84	53.26	52.84	48.78	29.79	39.42	48.01	7.65
Proportion of WFS	Chemically Bonded WFS											
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**Average**	**Stdev**
0%	45.53	49.2	54.51	58.25	49.13	49.32	50.26	56.75	48.86	42.93	50.47	4.77
5%	43	42.16	43.37	45.07	50.52	51.09	47.36	51.2	35.86	43.28	45.29	4.85
10%	45.55	44.45	44.22	39.12	44.6	49.49	45.74	56.58	39.43	43.12	45.23	5.00
20%	38.79	42.63	56.97	44.22	46.8	43.68	42.66	54.58	42.66	46.28	45.93	5.66
30%	46.98	60.37	56.73	59.73	50.13	51.4	55.68	45.03	50.2	45.98	52.22	5.60

Appendix 4.2: 14 Days Compressive Strength

	14 DAYS COMPRESSIVE STRENGTH (MPa)									
Proportion of WFS	Green WFS									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**Average**	**Stdev**
0%	56.5	54.58	50.15	46.48	52.88	45.27	52.68	57.12	51.96	4.37
5%	50.61	43.73	51.45	46.34	45.41	46.94	56.24	62.41	50.39	6.29
10%	47.86	56.08	49.74	52.72	42.7	44.2	57.25	59.11	51.21	6.09
20%	52.34	54.52	47.62	50.52	51.16	45.62	53.35	51.6	50.84	2.94
30%	44.26	50.51	49.32	40.82	45.61	47.62	46.8	48.88	46.73	3.13
Proportion of WFS	Chemically Bonded WFS									
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**Average**	**Stdev**
0%	56.5	54.58	50.15	46.48	52.88	45.27	52.68	57.12	51.96	4.37
5%	61.31	52.75	44.63	49.73	43.2	43.35	48.71	53.37	49.63	6.17
10%	46.89	46.94	54.85	52.72	46.63	53.61	59.69	57.49	52.35	5.07
20%	56.81	48.47	52.72	52.72	49.65	55.89	55.44	47.2	52.36	3.61
30%	42.53	49.42	51.87	59.52	40.68	44.47	42.77	41.72	46.62	6.52

Appendix 4.3: 28 Days Compressive Strength

	28 DAYS COMPRESSIVE STRENGTH (MPa)										
Proportion of WFS	Green WFS										
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**Average**	**Stdev**
0%	48.32	63.08	56.95	56.95	69.64	61.94	70.71	67.06	57.18	57.75	60.96	6.91
5%	45.48	52.83	55.52	55.07	50.45	56.1	51.31	51.05	40.22	44.34	50.24	5.29
10%	49.71	60.97	48.96	64.93	57.11	52.58	61.58	53.6	51.77	50.36	55.16	5.64
20%	54.03	47.33	61.03	62.97	58.53	50.57	59.45	53.47	50.28	51.99	54.97	5.22
30%	52.81	47.85	58.75	54.83	51.89	61.48	54.34	58.7	42.8	45.2	52.87	6.10
Proportion of WFS	Chemically Bonded WFS											
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**Average**	**Stdev**
0%	58.32	63.08	56.95	56.95	69.64	61.94	70.71	67.06	57.18	57.75	61.96	5.44
5%	52.42	49.88	49.08	40.1	60.1	54.69	55.79	55.87	58.66	49.91	52.65	5.79
10%	53.38	50.31	58.71	51.83	52.01	57.23	51.67	57.53	49.23	55.49	53.74	3.29
20%	48.25	52.91	58.89	47.76	58.5	57.48	57.39	57.9	39.67	45.62	52.44	6.73
30%	43.06	53.94	54.73	46.05	54.29	51.14	52.24	51.4	42.06	55.93	50.48	4.99

Appendix 5: Water Absorption of Concrete Paver Blocks

	WATER ABSORPTION (%)										
Proportion of WFS	Green WFS										
	W1	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**Average**	**Stdev**
0%	4.69	4.74	4.19	4.62	3.95	3.95	4.99	5.14	3.52	3.58	4.34	0.58
5%	4.49	5.11	3.85	3.96	6.53	4.63	5.01	5.03	3.55	3.65	4.58	0.90
10%	4.82	4.42	4.28	4.02	4.36	4.49	5.6	5.53	3.38	3.88	4.48	0.69
20%	4.9	4.79	4.25	4.4	4.56	4.38	5.19	5.2	3.81	3.4	4.49	0.58
30%	4.77	5.1	4.31	4.46	4.74	4.49	5.2	5.54	3.64	3.51	4.58	0.65
Proportion of WFS	Chemically Bonded WFS											
	W1	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**Average**	**Stdev**
0%	4.69	4.74	4.19	4.62	3.95	3.95	4.99	5.14	3.52	3.58	4.34	0.58
5%	4.73	4.99	4.11	4.41	4.30	4.26	5.63	5.42	3.79	3.55	4.52	0.67
10%	4.82	4.54	4.69	4.42	4.77	4.61	5.59	5.31	3.37	3.61	4.57	0.67
20%	5.20	4.86	4.02	4.46	4.26	4.66	5.48	5.28	4.10	3.48	4.58	0.64
30%	4.60	5.41	4.31	4.59	4.29	4.10	5.28	5.34	4.85	3.46	4.62	0.62