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Waste from stone industry as a cement additive towards a reduced carbon footprint of concrete

A Thesis submitted in the Partial Fulfillment for the Requirement of the Degree of Master of Science in Integrated Urbanism and Sustainable Design

by

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Yousef El-Shafie

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Abstract

Earthen resources are highly significant and ubiquitously used due to its low carbon footprint as it can simply be extracted from Earth with-out any shipping constraints. Stone is considered one of the most abundant resource on Earth. This exuberance in mountains spreads in rocks of various kinds. Its competitiveness with other materials is undeniable in terms of versatility, diversability, durability, emitability, permeability, hygienity and more. This led to the construction of many buildings with different architectural use, both in the stages of construction or finishing, and those buildings contributed greatly to highlight many civilizations across the world.

The main prospective is the natural characteristics of the stones. Thus, the optimal exploitation corresponds to their potentials and use possibilities. Ornamental stones include marble, granite and other refined stone types. The use of natural stones encompasses the extraction, transportation, manufacturing (sawing, polishing and cutting operations), shredding, installation and disposal process, which is a burden on the environment and causes health issues, in addition to economic issues.

The process of recycling waste from the global industries is very profitable. However, waste is still not exploited in the best way on the industrial and investment level. Thus, the generated stone waste could be implemented in concrete composites in different additive percentage in order to rationalize the use of natural resources.

The approach is to capacitate the concrete to absorb other industries waste and by-products. Therefore, the use of stone waste powder has a synergic effect positively on the environment, flora and fauna in addition to reducing the carbon footprint of cement, as a result of less energy consumption.

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List of terms and abbreviations

OPC	Ordinary Portland Cement
FA	Fly Ash
LS	Limestone
RA	Recycled Aggregates
MSP	Marble Sludge Powder
SCC	Self-Compact Concrete
CoV	Coefficient Of Variation
W/B	Water To Binder ratio
W/C	Water To Cement ratio
W/P	Water To Powder ratio
LOI	Loss On Ignition
TOC	Total Organic Content
SEM	Scanning Electron Microscopy
XRD	X-Ray diffraction
XRF	X-Ray Fluorescence
TGA	Thermo-gravimetric analysis
ITZ	Interfacial Transition Zone
UPV	Ultrasonic Pulse Velocity
PTFE	Polytetrafluoroethylene
SWOT	Strengths-Weaknesses-Opportunities-Threats
ROI	Return On Investment
ASTM	American Society for testing and Materials
ISO	International Organization for Standardization
EN	European Standards
BSI	British Standards Institution

1. Introduction

Earthen resources are highly significant and ubiquitously used due to their low carbon footprint as these resources can simply be extracted from Earth with-out any shipping constraints. In comparison to other materials in the construction of complex structures or compliant mechanical material approaches, either synthetic like steel and fibre tissues with their high carbon footprint or natural like timber, earthern resources are considered highly sustainable in many contexts.

Nowadays, we need a material that can sustain our overarching needs to extend vertically in high-rise buildings. However, conventional architecture has its own ingenuity on the level of low-rise buildings or even in vernacular architecture techniques. Stone is considered one of the most abundant resource on Earth. This exuberance in mountains spreads in rocks of various kinds. Its competitiveness with other materials is undeniable in terms of versatility, diversity, durability, emitability, low permeability, hygienity and more. This led to the construction of many buildings with different architectural use, both in the stages of construction or finishing, and those buildings contributed greatly to highlight many civilizations across the world.

The main prospective is the natural characteristics of the stones. Thus, the optimal exploitation corresponds to their potentials and use possibilities. Ornamental stones include marble, granite and other refined stone types. The use of natural stones encompasses the extraction, transportation, manufacturing (sawing, polishing and cutting operations), shredding, installation and disposal process, which is a burden on the environment and causes health issues, in addition to economic issues. (1)

The process of recycling waste from the global industries is very profitable. However, waste is still not exploited in the best way on the industrial and investment level.

Role of recycling in energy saving in some industries: (2)

- Aluminium recycling saves 95% of the energy that manufacturing needs from its original materials.
- Glass recycling saves 50% of the energy that manufacturing needs from its raw materials.
- Paper recycling saves 60% of the energy that making paper needs from raw materials.
- Plastic pack recycling reduces 2 billion tons of plastic delivered to the waste dumps.

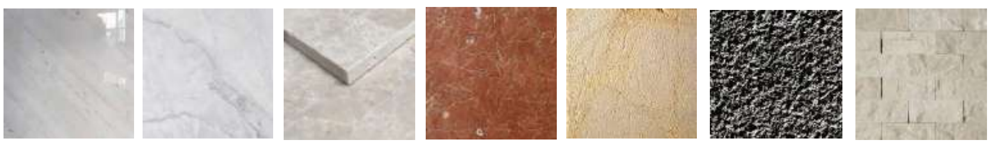
Therefore, it is necessary to investigate the nature of this waste and the most efficient methods of its reuse. With the appropriate treatments, recycling and re-use and safe disposal can be efficiently achieved.
This research study deals with the different types of stone waste and their possible use in concrete. Especially, the remnants of cutting and manufacturing processes.

Stone production line

1. Block extraction
2. Shipping to factory
3. Cutting / slicing into slabs or milling
4. Cutting / tiling and sizing
5. Polishing and chamfering

Generation of stone waste

Figure (1. 1): Types of polishing (waste production in polishing)



Polished **Honed** **Brushed** **Antique** **Sanded** **Bush hammer** **Split face**

The generated stone waste could then be implemented in concrete composites in different additive percentage to affect the physical and mechanical properties of concrete.

1.1. Research Problems

The resulting waste from the operations of extraction, cutting, and manufacturing of ornamental stone in the areas of stone production, led to the emergence of environmental pollution, which is the spread of large amounts of dust in the surrounding vicinities especially residential areas, in addition to problem of industrial waste. Such waste products can-not be easily disposed of , which led to land degradation, increase wastage of minerals, air pollution, water pollution, damage to flora and fauna and human resources displacement. Pollution is not limited to the areas of cutting and manufacturing ornamental stone only, but also the disposal of waste can export the pollution to the residents of the surrounding areas. The international natural stone production is about 100 million tons per year, and according to the expected growth ratio, it is expected to quadruplicate in the next 20 years. (3) Ornamental stone blocks mining and extraction at the quarries produce about 40 to 60 % waste. (4)

During the sawing process of blocks to slabs and then the polishing process, around 30 % of the whole block volume is turned into waste.
One cubic meter block when cut into 2 cm thick slabs using a 5 mm thickness blade, around 25% of the block volume is turned into waste.
The waste production is inversely proportional with the slab thickness, in case of cutting 3 cm thick slabs, around 50% of the block volume is turned into waste. (5), (6), (7)

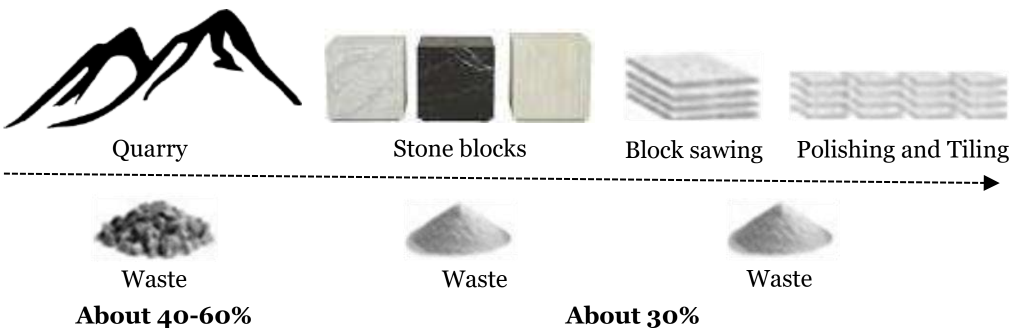


Figure (1. 2): Waste generation in stone production

The sawing process requires large amounts of water that acts as lubricants and coolants for the sawing blades, as well in the cleaning process.
The materials resulting from the processes of cutting and manufacturing of ornamental stone is an aqueous material called (**sludge / slurry**), which is the result of the cutting and manufacturing of ornamental stone with water.

Water component of it is relatively high, which necessitates the existence of transport vehicles equipped with tanks for transporting this material and dispose of it. According to (Mubarak, Friday June 27, 2003) (8), the sludge waste contains around 50% water content, which eventually is dumped or disposed of in landfills, agricultural lands or water streams, adversely having a negative effect on the environment and all the living habitats.
Stone sludge is highly dense, needing a period in the air to turn into minute-sized airborne particles, which can be inhaled by humans or animals as well. Thus, it must be buried in deep-buried landfills, which is a burden on the stone industry that threatens its competitive advantage and affects groundwater reserves.

Figure (1. 3): The generated stone sludge waste (Source: ARTEMIS)

It is necessary to find new ways to deal with stone waste and collect it in a healthy and clean environment. That can be achieved by finding machinery or industrial units to treat these wastes and to benefit from any aqueous or dry in the form of fractures and scatter of ornamental stone, either by mixing them or preparing them and using them as reinforcing materials and fillers. When these solid wastes are exploited or recycled, they will help to eliminate the pollution, protect the environment and support the industrial economies. To help create new job opportunities, increase industrial investments and support the economics of the stone industry, as well as the development of new environmentally friendly materials from processing plants and workshops waste.

Since the absence of environmental engineering methods to get rid of them and dispose of them causes many environmental and health problems, this study is devoted to discussing the problem of waste in the factories and workshops of ornamental stone in an attempt to answer the following questions:

1. What is stone waste?
2. What are the possible ways to recycle stone waste?
3. Can a proposed scientific methodology be inferred?
4. Can dried stone sludge be used as cement additive (in a similar way as limestone powder is used)?
5. What are the best ways to achieve economic and environmental benefit?

Some negative effects of not exploiting manufacturing waste appropriately:

1.1.1 Environmental Impacts

The spread of chest diseases amongst workers and residents, due to dust emerging from the process of cutting and manufacturing, which may lead to pneumonia and lung cancer and lead to death. The lack of care in the region of stone processing and extraction aggravates the problem of waste disposal.

1.1.2 Social Impacts

The lack of social awareness among workers in the region of proximity to the place of stone production increases the problems of environmental pollution. Moreover, dumping the waste in the nearby areas (and maybe within the region), leads to poor belonging and social engagement.

1.1.3 Economic Impacts

The amount of waste increases the price of the final product and affects the economics of the industry.

The research problem could be summarized in the limited applications for the efficient exploitation of stone waste under the umbrella of clear rules and standards to deal with the waste of manufacturing processes as well as their negative impacts on the environment, society and economy of the industry.

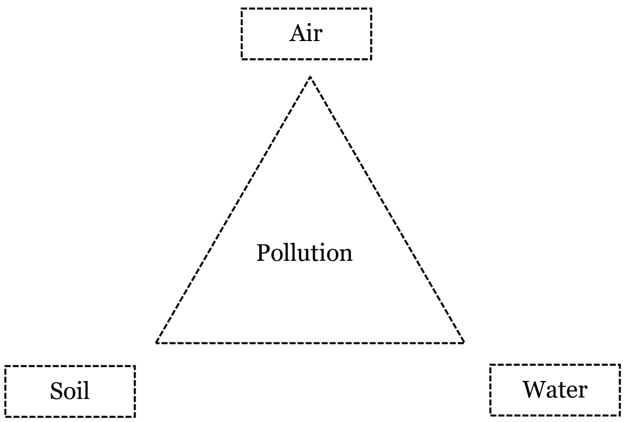


Figure (1. 4): Environmental pollution

1.2. The Main Objective of the Research

The purpose of this research is to extrapolate practical, feasible and legal techniques for the recyclability and reusability of materials waste. In particular, the recycling of construction waste, with a practical application focusing on to the stone material to investigate the environmental, social and economic benefits.

In order to eliminate the environmental pollution resulting from the stone industry in an efficient manner that benefits the economic and social aspects.
Thus, investigating the possibility of using the waste material in the manufacture of other materials that can be used in different industries; as in concrete production reducing both the environmental impact and production and end-cost.

2. Previous studies

2.1. Products from stone waste

2.1.1. Concrete composites and paving blocks with up to 40 % marble waste residues as an aggregate in the concrete mixture, satisfying results obtained with regards to the quality of cured concrete.

As per **Hebhoub et al.**, when the substitution of natural coarse aggregate with marble waste aggregate at rates 25%, 50% and 75% with constant water/cement ratio of 0.5 was investigated.

The results showed an enhancement in both the compressive and tensile strengths. However, the workability decreased with the increase in replacement rates; as the water absorption rates of marble waste aggregates are less than that of the natural aggregates. It was concluded that marble waste could be used as an aggregate substitute for concrete in brick industry, road construction and landfills. (9)

These results were in agreement with those obtained by **Almeida et al.**, when the mechanical properties of concrete mixtures while substituting semi-liquid natural stone waste (slurry) with sand aggregate at percentages of 0%, 5%, 10%, 15%, 20%, 34%, 67% and 100% by volume were investigated. The compressive strength at an age of 7 and 28 days, splitting tensile strength and modulus of elasticity at the age of 35 days were tested.

The results showed that the substitution of 5% of the sand content by stone slurry enhanced the compressive strength, splitting tensile strength in addition to the modulus of elasticity. (10)

Moreover, analogous results obtained by **Binici et al.**, when the mechanical properties of concrete while replacing fine sand aggregates with marble and limestone dusts as additives at replacement rates of 5, 10 and 15% at 7, 28, 90 and 360 days, and Sodium Sulphate resistance at 12 months were investigated.

The results indicated an enhancement in the mechanical properties of concrete mixtures when compared with conventional concrete; thus increased compressive strength, abrasion resistance, and sodium sulphate resistance with the increasing amount of marble dust. (11)

While, **Omar M. et al.**, investigated the replacement of limestone waste with sand at percentages of 25%, 50%, and 75% in the concrete mixes, in addition to the replacement of marble waste powder with sand at percentages of 5%, 10% and 15%.
The results showed that the replacement of limestone waste with sand at replacement rate up to 50% and marble waste powder with sand at replacement rate up to 15% did not affect the workability of concrete mixes, in addition to improving the compressive strength and the indirect tensile strength. (12)
Furthermore improvement achieved by **Corinaldesi et al.**, when the replacement of marble powder with 10% of sand while adding super-plasticizing admixture was investigated.
The results showed an improvement in the compressive strength of concrete after the addition of the super-plasticizing admixture, which compensated the high water demand of marble powder. The mechanical strength was enhanced due to both the filler effect of marble powder and the implementation of super-plasticizing admixture, at the same workability level at curing age of 28 days. (13)
These results were reinforced with those obtained by **Demirel et al.**, when the replacement of the marble waste dust with the fine sand that pass through the 0.25 mm sieve at percentages of 0, 25, 50 and 100% by weight was investigated. The compressive strengths of the samples at the curing ages of 3, 7, 28 and 90 days were recorded. In addition, the porosity value, Ultra-Sonic Pulse Velocity (UPV), dynamic modulus of elasticity (Edin) and the unit weights of the series were recorded.

The results showed an enhancement in the mechanical and physical behaviour as increasing the percentages of marble dust at all curing ages. It was observed that the strength of concrete increased as the marble dust content was increased. The addition of marble dust enhanced the cement hydration process due to its filler effect that decreases the porosity of hardened concrete and consequently increasing the ultrasonic pulse velocity. Finally, the highest dynamic modulus of elasticity has been recorded with the highest marble dust addition that gave the highest strengths as well. In the below microscopic graph, it illustrates the CH ($Ca(OH)_2$) morphology in specimens without marble dust powder and with 50 % marble dust powder. Whereas, the distribution of CH is observed as a large and euhedral crystals in specimens without marble dust powder, but smaller and well distributed in specimens with 50% marble dust powder. (14)

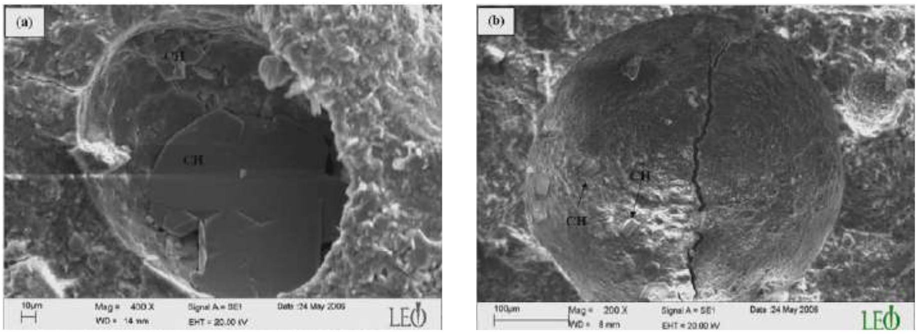


Figure (2. 1): Scanning Electron Microscopy micrographs (SEM)

(a) without marble dust powder (b) with 50% marble dust powder

Also, the results were in agreement with those of **Hamza et al.**, when the replacement of marble and granite waste powder of different sizes with conventional coarse and fine aggregates at percentages up to 40% was investigated.

The results showed an increase in the compressive strength of concrete using granite waste powder 33%, and 48% greater with that of marble.

It was concluded that the optimum results obtained for cement brick samples using granite waste sludge at 10% replacement. Water absorption requirements were only achieved at replacement rates of 0, 10 and 20%. However, that of the abrasion resistance was achieved at all rates. (15)

On the contrary, **Baboo et al.**, investigated the partial replacement of cement and usual fine aggregates with marble granules powder by varying the percentages at 0%, 5%, 10%, 15% and 20%.

The results showed that the increase in the replacement of marble powder with cement decreased the compressive strength values of the specimens. Whereas, the increase in the replacement of marble powder with fine aggregates increased the compressive strength values of the specimen, in addition to the increase in the workability and compressive strengths of the mortar and concrete. (16)

These results are incompatible with those obtained by **Yılmaz et al.**, when the utilization of marble dust with Portland cement clinker CEM I and CEM II with blending ratios of 2.5%, 5.0%, 7.5% and 10% by weight was investigated. The mortar specimens at curing ages of 7, 28, and 90 days were tested.

The results showed that the use of marble waste dust could be utilized with cement as an additive at a blending rate of 10% without affecting the setting time of cement paste. Moreover, the addition of marble waste dust decreased the specific gravity as well as the specific surface of mortar specimens. However, it enhanced the compressive strengths of mortar specimens in comparison to those of Portland cement only. It was concluded that the utilization of marble waste dust saves 10% of the cost of cement production. (17)

Whereas, **Mishra et al.**, investigated the partial replacement of marble waste dust with Portland cement clinker at percentages of 0%, 2.5%, 5.0%, 7.5% and 10% by weight.

The results showed that under microscopic investigation there are differences in free CaO, silica, aluminate and ferrite compositions, in addition to the sizes and distribution between the blended cement and ordinary cement. Moreover, it was observed an increase in the fineness of blended cement. The hydration rate with blended cement was faster than its counterpart. It was concluded that cement with marble dust powder increased the strengths of concrete. (18)

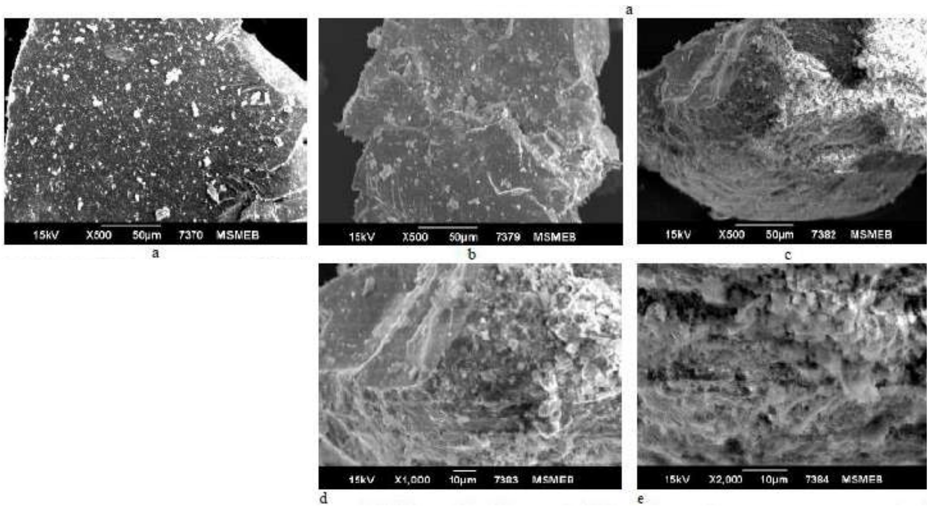


Figure (2. 2): Scanning Electron Microscopy image (SEM)

Partial replacement of marble waste dust with Portland cement clinker at percentages of 0% (a), 2.5% (b), 5.0% (c), 7.5% (d) and 10% (e) by weight.

Moreover, **Arshad et al.**, investigated the replacement of marble sludge waste with cement at percentages up to 100%.

The results showed a satisfying compression strength of more than 3000 psi and a tensile splitting strength of 28 tones at a partial replacement rate of 7% marble waste sludge with cement, in addition to a slight decrease in the workability of concrete. It was concluded that due to the high calcium content in the marble sludge waste, it could be an easy and cheap material in construction; the produced concrete can be used safely in on-road bearing structures. (19)

These results were compatible with those of **Sharma et al.**, when the partial replacement of marble dust with cement at percentages of 5, 10, 15, 20, 25 and 30% was investigated. Then, the compressive, split tensile and flexural strength of concrete were compared, in addition to its workability and durability.

The results showed an enhancement in the slump of concrete mixes as the replacement of marble dust increased, in addition to an increase in the unit weight of the concrete due to the high specific gravity of marble powder. Thus, it has facilitated the hydration process. It was concluded that the replacement enhanced the mechanical and physical properties. However, the porosity of the concrete decreased due to the efficient micro-filling ability. (20)

In addition to those achieved by **Jashandeep Singh et al.**, when the partial replacement of waste marble powder M25 grade with cement at replacement rates of 0%, 4%, 8%, 12%, 16%, and 20% was investigated.

The results attained maximum compressive and tensile strength at a replacement of 12% of waste marble powder with cement. It was concluded that the hydration reaction is highly dependent on the strength, type and amount of cement used in concrete. Besides, the strength of concrete is adversely affected by the increase of the percentage of marble waste powder. (21)

Also, **Mashaly et al.**, has supported the same results when the effect of substituting cement by marble sludge waste at 0, 10, 20, 30 and 40% by weight was investigated on the physical and mechanical properties of fresh and hardened cement composites and some concrete mixtures.

The results showed an optimum improvement in the physical and mechanical properties of hardened cement composites and conventional concrete mixtures at a substitution rate of 20%. It was observed a linear increase in water demand, abrasion resistance, water absorption and apparent porosity increased directly proportional with the increase in the marble aggregate content, but inversely affecting the density and compressive strength. (22)

These results were in agreement with those obtained by **Aliabdo et al.**, when the replacement of marble dust powder with cement and with sand at replacement ratios of 0.0%, 5.0%, 7.5%, 10.0% and 15% by weight was investigated. The water to powder ratio (w/p) was 0.50 when replaced with cement and water to cement ratio (w/c) was 0.40 when replaced with sand. The physical, mechanical and chemical properties of cement and concrete, in addition to the TGA, XRD and SEM analysis were also investigated.

The results showed an enhancement in the compressive strength at replacement ratios up to 15% of marble dust powder with cement. Furthermore, more improvement in the compressive and tensile strengths when replacing marble dust powder with sand were obtained.

It was concluded that the replacement up to 15% enhanced the steel-concrete bond strength. Moreover, there is no noticeable effect during the hydration process, nor in the chemistry of the cement paste, and finally nor in the setting time of the cement paste with the replacement rates. (23)

Analogous results achieved by **Rana et al.**, when the feasibility of using partial replacement of marble slurry with Portland cement, at percentages up to 25% was investigated. In order to evaluate the strength, permeability, porosity, morphology, resistance to chloride migration, carbonation and corrosion.

The results showed optimal outcome for the replacement at 10% using concrete of requisite strength and enhanced durability. Furthermore, the high surface area of marble sludge particles reduced the workability of concrete. The filler effect of marble slurry granules occupied the voids and densified the concrete matrix, improving its resistance to permeation, chloride migration and corrosion. (24)

While, in different conditions, **Rodrigues et al.**, investigated the mechanical behaviour of concrete when replacing marble sludge waste with cement at replacement rates of 0%, 5%, 10% and 20% by volume, with the incorporation of superplasticizer admixtures.
The results showed an enhancement in the workability of the mix, which can be attributed to the usage of the superplasticizer admixtures. However, the bulk density, the compressive strength and abrasion resistance have decreased as the replacement rates increased. Moreover, the modulus of elasticity, ultrasonic pulse velocity have decreased slightly with the increase in the replacement rates.
It was concluded that 10% replacement of marble sludge waste with cement does not affect its mechanical behaviour, but could be enhanced with the use of superplasticizer admixtures. (25)
These results were incompatible with those achieved by **Topçu et al.**, when the replacement of marble sludge waste with cement in the production of self-compacting concrete at replacement ratios up to 100% was investigated.
The results showed that the replacement of marble sludge waste with cement enhanced the filling ability of self-compacting concrete. On the contrary, the compressive strength of concrete with marble sludge waste replacement was reduced along with low water-cement ratios, which led to a reduction in the modulus of elasticity as well. However, the strain capability, which corresponds, to the maximum stress was increased. (26)

Furthermore **Atiyeh et al.,** investigated the incorporation of bottom ash and marble powder with cement at percentages of 20 and 25% by weight, for the fresh and hardened concrete properties at curing ages of 7, 28 and 56 days. Then, the physical and mechanical characterization and sulphate resistance, in addition to the workability, strengths, and durability properties of the marble-bottom ash-cement were analyzed.

The results showed an improvement in the unconfined compressive strength, flexural strength, mini-slump, flow table, water absorption, apparent specific gravity, bulk specific gravity and porosity. Moreover, sodium sulphate expansion test results improved with marble waste dust but declined with the bottom-ash incorporation. The investigated composites were evaluated, according to the (ACI) report and (ASTM) standards, and compared with pure paste composites. (27)

On a wider scope **Misra and Gupta**, investigated the flexural strength and flexural creep characteristics of the flooring tiles containing marble powder. Four different mix proportions with a ratio of cement to marble powder of (1:5 to 1:8) respectively were prepared. The tests were conducted after a period up to 81 days.

The results showed a satisfying flexural strength for the tiles having marble powder content up to approximately 87%. It was concluded that the addition of marble powder led to a reduction in the creep deformations of the tiles. (28)

Whereas, these results were reinforced by **Soliman et al.**, when the partial replacement of marble sludge waste with cement on the concrete properties was investigated, in addition to its influence on the behaviour of reinforced concrete slabs.

The results showed that the replacement of small amounts of marble sludge waste with cement increased the workability, compaction and strengths of concrete. However, replacing marble sludge waste with cement at percentages up to 7.5% decreased the indirect tensile strength as well as the modulus of elasticity. Moreover, the replacement of marble sludge waste with cement at percentages up to 5% led to the increment of the initial crack and the ultimate load values, in addition to decreasing the deflection of reinforced concrete slabs compared to the control slab. It was concluded that the replacement of marble sludge waste with cement at percentages up to 5% increased the stiffness of concrete slabs. (29)

On the other hand, **Hameed et al.**, investigated the marble sludge powder from marble processing plants and crusher rock dust from stone crushing industries, to observe the effect of the latter addition on the durability of Self-Compacting Concrete. Several tests including water absorption, water permeability (flow) were conducted. The obtained results were compared with reference river sand and normal concrete.

The results showed a reduction in the permeability but the compressive strength remained the same. It was concluded that the incorporation of marble sludge powder enhanced the matrix in concrete, making it less dense and less porous. However, the Ultrasonic Pulse Velocity increased linearly with the age of concrete, in addition to the increase in the target mean strength of the concrete. (30)

More investigations were carried out by **Ergun et al.**, when the effects of using diatomite and marble waste powder as partial replacement of cement on the mechanical behaviour of concrete were investigated. The replacement rates of cement in concrete specimens were by weight 10% diatomite, 5% marble waste powder and 5% marble waste powder + 10% diatomite. The tests were conducted at curing ages of 7, 28 and 90 days.

The results showed an improvement in the mechanical strengths and the compressive strengths of concrete mixtures, when replacing cement with diatomite and marble waste powder separately or together using a super plasticizing admixture. (31)

These findings agree with those by **Gencel et al.**, when the feasibility and the effects of the replacement of aggregates with marble waste on the physical and mechanical properties of concrete paving blocks using different types of cement were investigated.

The results showed an improvement in the durability of paving blocks containing higher marble aggregate content. Thus, the more marble aggregate content results in more water demand, due to the higher specific surface of fine marble aggregates, in addition to the W/C ratio increment and abrasion resistance improvement.

On the contrary, the dry density was affected adversely due to the increase in the water content of concrete mixture. It was concluded that higher-grade cements result in a higher resistance to the freeze-thaw cycles, as well as higher elasticity modulus of the concrete. (32)
However, **K. Barani et al.**, investigated the use of granite and marble stone sludge, ground quartz powder, ground waste glass, and an unsaturated polymer resin by the vibratory compaction method in the production of artificial stone slabs of densified structures.
The results showed that the water absorption, the density, the flexural tensile and compressive strengths decreased with the increase in the stone sludge waste content. Furthermore, the artificial stone slabs produced by mixing 50% of stone sludge, 12% of ground quartz, 25% of waste glass, and 13% of resin under a compaction pressure of 12 MPa, a vibration frequency of 30 Hz, and vacuum conditions at 50 mm Hg had a good density, water absorption, and flexural, compressive, and tensile strengths compared to the natural stones. Therefore, the slabs could be used as a construction material for cladding walls or paving floors. (33)

While, **Alzboon et al.**, investigated the possibility of replacing the stone cutting waste slurry with potable mixing water.
The results showed that 50 % replacement of stone cutting waste slurry with potable mixing water could improve the compressive and flexural strengths of concrete and cement mortar mixes. However, the same replacement rate caused a reduction in the tensile strength, as well as a decrease in the workability concrete. It was concluded that the replacement to some extent could improve the characteristics of concrete and mortar mixes. (34)

2.1.2. **Concrete brick making** with up to 50 % marble waste residues as an aggregate in the concrete mixture, satisfying results obtained with regards to the quality of non-bearing concrete bricks.

As per **Alzboon et al.**, when the replacement of marble waste of different sizes, with coarse and fine aggregates at percentages up to 40%, in the manufacturing of concrete bricks and terrazzo tiles was investigated. In addition, the replacement of dolomite with coarse aggregate and slurry powder with fine aggregates was tested.

The results showed that all the results obtained for the transverse strength, water absorption, and tile measurements for all of the tested samples comply with the international standards. However, a decrease in the transverse strength as the ratio of the added marble waste sludge increased was observed. While, an increase in the water absorption as the ratio of the added marble waste sludge increased. It was concluded that replacing up to 50% of marble waste sludge with aggregates in concrete mixtures could successfully produce non-loaded bearing bricks. (35)

On the other hand, **Turgut et al. 2007**, investigated the potential use of limestone powder wastes and wood sawdust wastes in the production of a low-cost and lightweight composite as a brick building material.

The results showed that the replacement of limestone powder wastes and wood sawdust wastes does not adversely affect the concrete properties. Furthermore, this composition resulted in a comparatively 65% lighter brick than the conventional concrete brick. It was concluded that the concrete with 30% replacement rate of limestone powder wastes and wood sawdust wastes obtained satisfying results in the compressive strength, flexural strength, unit weight, ultrasonic pulse velocity (UPV) and water absorption values with regards to the international standards. (36)

Moreover, **Turgut P. et al. 2008**, later investigated the use of limestone powder wastes and glass powder in the production of masonry blocks.

The results showed an increase in the compressive and flexural strength (rupture modulus rate) of masonry blocks with limestone powder wastes and glass powder when reducing the W/C ratio in the mixture, which satisfies the international standards. (37)

Furthermore, **Turgut P. et al. 2010**, investigated the use of limestone powder wastes and fly ash at percentage rates of 10, 20 and 30% by volume in the production of masonry composites. The compressive, flexural strengths, ultrasonic pulse velocity were tested at curing ages of 7, 28 and 90 days. Moreover, the Density, water absorption and thermal conductivity values were tested at curing age of 28 days.

The results showed that the 20% replacement of fly ash obtained the optimum results with regards to the international standards for load-bearing and non-load-bearing concrete masonry units. It was concluded that this composition could be used to produce a new type of an economical masonry block. (38)

Then, **Aukour et al.**, reinforced these results, when the substitution of marble and granite sludge with fine aggregates in producing eco cement blocks was investigated.

The results showed optimum outcome when using portions up to 50% of fine-sized marble and granite sludge and medium and coarse sized gravel of limestone. However, the whole substitution of fine sand or fine limestone affected the produced material adversely. It was concluded that the marble and granite waste could be implemented in proportions in several brick compositions and particularly in clay-based materials production. The incorporation of marble and granite sludge enhanced the physical, chemical and mechanical strength of the produced industrial brick. (39)

These results were compatible with those of **Bilgin et al.**, when the behaviour of brick compositions with addition of marble waste powder at percentages up to 100 wt. % was investigated. Then, their mechanical, mineralogical and physical properties, i.e. shrinkage, bloating, weight changes, water absorption, porosity, and bulk density were studied, when sintering in an electrical furnace for 3 hours at 900, 1000 and 1100 °C. The results showed a decrease in the weight but an increase in the size as the addition rates increased. It was concluded that 10% by weight of marble powder could be added to an industrial brick mortar without affecting the technical properties of the brick. On the contrary, the more marble waste powder added over the 10 wt. %, the higher water absorption rates recorded, but the lesser mechanical properties achieved. It was concluded that the hardness of the brick increased directly proportional with the addition of marble waste powder. Whereas the porosity increased with the amount increased of marble powder in the brick, as well as with the sintering process, as shown in the scanning electron microscopy results. This is ascribed to the release of carbon dioxide gas in the calcination process, due to the rise of temperature. (40)

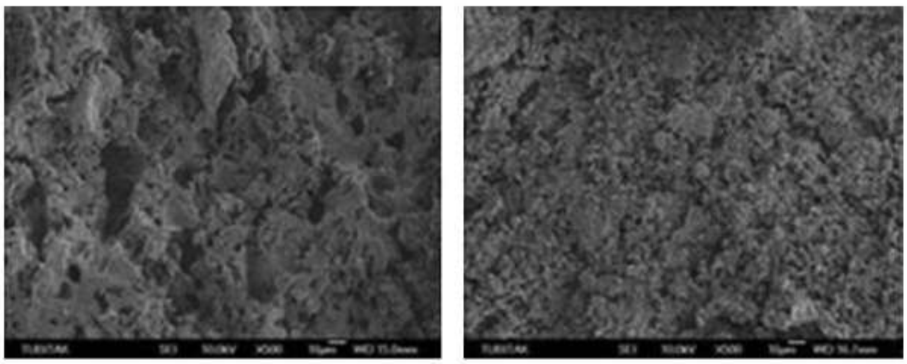


Figure (2. 3): Scanning Electron Microscopy image (SEM)

50 : 50 wt. % Marble powder : Brick mortar At 1100 °C

70 : 30 wt. % Marble powder : Brick mortar At 1000 °C

Whereas, **Saboya et al.**, investigated the mechanical characteristics of the bricks, when mixing clayey soil with marble powder at percentages 0%, 5%, 10%, 15% and 20% in weight.
The results showed a correlation between water absorption, porosity, specific gravity and strengths with marble waste powder and the firing temperature. The mechanical strength decreased with the increase of marble waste powder addition, on the contrary the freeze-thaw durability and abrasive wear resistance increased. It was concluded that the best results were obtained when using 15-20% of marble waste powder in red ceramic raw material, where the limit for construction purposes, industrial scale and commercial use was at 15%. (41)

In similar conditions, **El-Mahllawy et al.**, investigated five different materials clay, sand, marble cutting waste, while ordinary Portland cement and hydrated lime acted as stabilizers, at curing ages of 14 days and 28 days. All the material used passing through a 300-micro diameter sieve. The laboratory-made unfired cylindrical clay specimens were analyzed by X-ray diffraction (XRD) for mineralogical characterization. The chemical composition of the raw materials (major oxides) used was determined by X-ray fluorescence (XRF).
The results showed that as the curing period increased, the water absorption decreased, however the bulk density of the clay-based specimens increased. It was concluded that the compressive strength has increased by 50% significantly with an optimum water content range between 10–13% for static compaction. (42)

While, more investigations were carried out by **Arboleddas et al.**, when the manufacturing of lighter structural clay ceramics using marble cutting dust and packaging paperboard/polyethylene waste was investigated.

The results showed a feasible outcome in accordance to the percentages used and temperatures. Moreover, an improvement in the strengths of the tested specimens were observed. It was concluded that this investigation requires more improvements. It just opens the door for more comprehensive microstructural characterization work to identify the mechanisms of sintering and more mechanical optimization of some compositions and dosages. (43)

2.1.3. Compatibility of marble sludge for recycling in some applications of relevance: (44), (45)

a) **Cement production** where limestone is considered one of the major components required in the mixture. Subsequently, the high percentage of calcium carbonate in the marble sludge powder, besides the presence of Silicon dioxide among other metal oxides could be either incorporated in the cement manufacturing or later as a non-detrimental additive with cement. (46), (47)

b) **Ceramics industry (Red clay ceramics)** by incorporating the marble sludge powder up to 45% in the production of Ceramics forms, pottery and artifacts. (48), (49), (50), (51), (52), (53)

c) **Brick industry** by incorporating the marble sludge powder up to 50% in the production of claay bricks. (54)

d) **Paper industry** involves the addition of limestone powder at percentages up to 10% either as fillers and pigments in the manufacturing stage or in the polishing stage. Thus, the finely ground dried marble sludge powder could be incorporated in the industry, due to the high percentage of calcium carbonate which has a high whiteness index, in addition to the possibility of using it as fillers and pigments in the water paints industry. (55)

e) **Plastic industry** requires significant amount of fillers according to the product. Thus, dried fine marble sludge powder could be incorporated as a filler in the polypropylene production, in addition to the production of polyvinyl chloride (PVC) production where calcium carbonate is used as a filler. (56)

f) **Fertilizers manufacturing** where fine marble sludge powder with its high calcium carbonate percentage is used to produce calcium nitrate. Which is considered as a main ingredient in fertilizers. (57), (58)

g) **Herbage and animal grass** mostly contain up to 10% calcium carbonate. Meanwhile, selected white dried fine ground marble sludge powder with low metal content and high purity (in-toxicity) could be used due to its calcium content. (59)

h) **Desulphurisation of fumes from thermoelectric plants**, due to the high sulphur oxides produced, which has a negative effect on the health and the environment. Thus, marble sludge could be used with its high percentage of calicum carbonate to initiate the desulphurisation process. (60), (61)

i) **Bituminous mixes in Asphalt pavement**, as the larger schattered pieces could be used as 94% aggregates with 6% bitumen. (62), (63)

j) **Marble resin products** are manufactured by mixing the white calcium carbonate fine particles of different size gradients with polyester resin, to manufacture decorative plates. (64)

k) **Manufacturing of Al-Mg-Si alloy foam**, due to the presence of aluminium oxide, magnesum carbonate and silicon dioxide. (65)

l) **Slovay soda ash production**, by selecting marble sludge powder of high calcium carbonate percentage of not less than 90% as a reagent, magnesium carbonate percentage of not less than 6% and oxides of less than 3%. Then, by heating it at 1000 °C to initiate the calcination process to turn calcium carbonate into sodium carbonate (Na_2CO_3). The Slovay soda ash could be used to recover the lead from flat batteries. (66)

m) **Iron and steel manufacturing** requires the addion of (limestone) flux as reducing agent to facilitate the smelting process, decomposing the iron ore into slag and metal base. (67)

2.2. Research Hypothesis

The post-dehydrated material produced in the stone industry as waste has geometric properties of sandy soils as well as a high percentage of calcium carbonate ($CaCO_3$), which is considered as a bonding material and has certain advantages for some industrial and structural applications. Therefore, the research assumes the possibility of using the generated waste in the building materials industry and minimizing or eliminating its resulting pollution.

2.3. Research Design

The research deals with the problems of the waste of building materials, with a focus on the processes of the manufacturing of marble and granite and utilizing their waste to be recycled and processed in a way that commensurate scientifically with the local reality.

This study aims to achieve an industrial ecology from the environmental and sustainable point of view according to the research information. Therefore, the study will be limited to the collected samples taken from randomly selected marble and stone factories. These factories deal with all types of ornamental stones commonly used.

2.4. Research Methodology

The study of the waste properties in stone processing plants and its environmental effects is one of the main concerns of many governmental bodies as follows:

Environmental Affairs, which deals with environmental pollution and natural resources.

Agricultural Affairs and Agrarian Reform due to the invasion of the remnants of stone factories and the protection of plants and animals.

Industrial Affairs, which is interested in the manufacture of building materials and sand resources as a construction material.

Tourism Affairs, which deals with touristic places and monuments near stone factories, which can directly be affected.

Oil and Mineral Resources management, which deals with the manufacture of stone as a natural resource.

Health Affairs, which deals with human health.

Investors at the local level and worldwide, who are interested in this issue in order to invest in the waste of stone factories, in order to benefit from them economically.

The research deals with the recyclability, re-usability of materials waste with a focus on marble and granite manufacturing processes through two main sections:

1. Theoretical study invoking an inductive analytical method.
2. Applied study conducting an experimental testing method.

2.5. Applied Studies Design

It includes the study of how to exploit the waste resulting from the cutting and manufacturing of marble, granite and stones (**sludge or slurry**) by focusing on some of the main points, including waste recycling and its use in many areas of construction and finishing and exploitation in many areas of architecture in construction and decoration.

The analysis and description of the resulting waste from the cutting of marble, granite and stones in different forms:

- An investigation on the substances of the waste sludge in terms of various properties.
- An analytical study on these wastes to know their components and the difference between them and the natural raw material.
- Practical and experimental alternatives of the stone sludge waste in many products.

The stage of implementation and scientific application:

- Components of the material.
- Methods of implementation.
- Tests.
- Economic studies.
- Environmental benefits.
- Output the final product.

Analyzing the inputs and outputs in a matrix (comparative analysis), to study the feasibility of each.

State of the art in concrete technology

Concrete industry is responsible for consuming natural resources and high amounts of energy, in addition to the carbon dioxide emissions. Thus, concrete is a high carbon footprint product, with an expensive component like cement.
The approach is to capacitate the concrete to absorb other industries waste and by-products, as in the matrix table below, in order to reduce the negative effect on the environment, flora and fauna.
The development in the concrete technology is to incorporate the by-product of stone waste as cement replacement (additives). Thus, rationalizing the use of natural resources. Many researchers carried out researches to replace cement with additives like **pumice, nutshell, wood and tea waste, fly ash, blast furnace slag, silica fume, rice husk ash, diatomite and perlite**.

The matrix conducts the factorial design analysis of each product that can be manufactured using stone sludge. The data is interpreted using computational methods and experiments to benchmark which and where it could be used.

	Content	Order	Amount %	Addition	Process	Manufacture	Place						
Cement composites													
Ceramics													
Bricks													
PVC pipes													
Paint industry													
Agriculture products													
Bituminous mixes													

Table (2. 1): Factorial design analysis

3. Standards and specifications

3.1. Cement, mortar and concrete conformities and standards

All developed countries have their own standards that comply with the international norms regarding testing and experimenting of concrete also with regarding to its additives.
Earlier, the British Standards Institution (BSI) was the prevailing norm for most of the countries all over the world, and then came the American Society for Testing and Materials (ASTM). In 2000, The European Standard (EN 197) was adopted by the following European countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. It was meant to facilitate the trade between the European countries and unite on one standard. Thus, the European standard in addition to the standards for test methods (EN 196) and assessment of conformity (EN 197-2) would prevail expectedly over most of the national (or regional) cement standards all over the world. (68)

In this research, all the methods, tests, assessments and additives comply with the European standards DIN EN XXX.

Here are some examples of the European standards that relate to this research
EN 196-X: Methods of testing cement
EN 197-1: to include low heat common cements
EN 197-X: Low early strength blast furnace cements
EN 413-X: Masonry cement
EN 450-X: Fly ash for concrete
EN 645: Calcium aluminate cement
EN 14216: Very low-heat special cements
EN 459-1: Building lime
EN 13282: Hydraulic road binders

DIN 1164-10: Special cement
EN 206 (2013)+A1 (2016): Concrete
EN 933-9 (2009)+A1 (2013): Tests for geometrical properties of aggregates
EN 933-10 (2009): Tests for mechanical and physical properties of aggregates
EN 1097-7 (2008), EN 1744-1+A1 (2009): Tests for chemical properties of aggregates
EN 12620 (2002)+A1 (2008): Aggregates for concrete
EN 13639 (2017): Determination of total organic carbon in limestone

Testing of fresh concrete
NP EN 12350-2 (2009): Slump test
NP EN 12350-6 (2009): Bulk density

Testing of hardened concrete
NP EN 12390-3 (2011): Compressive strength at 7, 28 and 56 days
NP EN 12390-6 (2011): Splitting tensile strength at 28 days
LNEC E-397 (1993): Modulus of elasticity at 28 days
NP EN 12504-4 (2004): Ultrasonic pulse velocity
DIN 52108 (2008): Abrasion resistance at 91 days

Besides the European standards (EN) that has a great significance around the world, the American standards (ASTM) are still of importance in many countries, therefore in some parts of the research, both norms were used to conform the obtained results.

Here are some examples of the American standards that relate to this research

C33: Specification for Concrete Aggregates
C109/C109M: Test Method for Compressive Strength of Hydraulic Cement Mortars
C114: Test Methods for Chemical Analysis of Hydraulic Cement
C150: Specification for Portland cement
C151: Test Method for Autoclave Expansion of Hydraulic Cement
C157/C157M: Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C185: Test Method for Air Content of Hydraulic Cement Mortar
C188: Test Method for Density of Hydraulic Cement
C204: Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus
C226: Specification for Air-Entraining Additions for Use in the Manufacture of Air-Entraining Hydraulic Cement
C227: Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C430: Test Method for Fineness of Hydraulic Cement by the 45-µm Sieve
C441: Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction
C618: Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C670: Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
C778: Specification for Standard Sand
C1012: Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C331-07: Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete

3.2. Sampling

The scope of the research is dealing not only with marble and granite cutting waste but other building materials that are mostly involved in processing factories and plants.

According to an interview with Mr. Albrecht Lauster the managing director of Lauster Steinbau Gmbh Stuttgart Germany “In Maulbronn we process several types of rocks at the same time, mostly sandstone and limestone, each with different types of material. A separate rock sludge is not possible. You can remove the rock sludge in its mixture, which results from current processing operations with different materials, as sludge and then use it for your purposes. In our Krastal quarry in Austria, we process the crystalline marble that is there. There it would be possible to remove unmixed sludge material”.

The samples were collected at Karl Schäffer Steinmetzbetrieb GmbH Stuttgart Germany, according to Mr. Matthias Schäffer the owner “The cutting process usually encompasses many stone types that are randomly processed in different treatment stages; on a wide range, stone sludge may include Marble, Granite, Natural stone (Cosentino, Sapienstone…), Ceramic, Porcelain, Artificial sintered stone slabs (Lapitec, Silestone, Dekton…)”.
In the sampling process, four different samples taken from four different weeks randomly.

Sludge separation using Cyclone separators

The by-product of cutting, shaping and polishing of the processed stone is randomly collected as a wet powder.
The collection process includes a potential vortex to separate stone fine particles from water; the centrifugal gravity pushes the particles to the walls of the cyclone and then precipitate to the bottom to be collected. (69)

The stone sludge accumulates randomly inside with high content of water. Whereas, the sludge is compressed in packets to be ready for disposal, as shown in figure (3.1).

Figure (3. 1): Waste collection

Left: Collection of sludge

Right: (Cyclone) illustration of the internal operation

3.3. Preparation

The collected samples were marked with dates and named as follows Y_00, Y_01, Y_02, and Y_03. Each was heated or air-dried at 105 °C. It was observed that after drying out the samples, it formed lumps of sludge.

Wet state Dry state Ground state

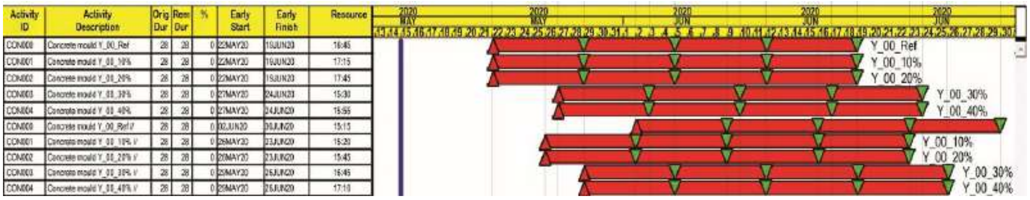
Figure (3. 2): Sample preparation

The dried stone sludge was ground and dis-agglomerated on a hammer-mill rotor machine, passing through a 0.25mm (25-micrometre sieve), without affecting the sample particle sizes to form a homogenous mixture. A sample of each specimen was taken to the chemical analysis.

Figure (3. 3): Grinding machine

3.4. Casting

It starts with moulding 3 prismatic specimens of concrete in a stainless steel moulds 40*40*1600 mm in size for each sample (Y_00), (Y_1), (Y_2) and (Y_3) for the mechanical behaviour test each for a cement replacement with 0, 10%, 20%, 30%, 40% of dried stone sludge, according to (DIN EN 196-1:2016-11), (EN ISO 1101), (EN ISO 1302).



Activity ID	Activity Description	Orig Dur	Rem Dur	%	Early Start	Early Finish	Resource
CON000	Concrete mould Y_00_Ref	28	28	0	22MAY20	19JUN20	16:45
CON001	Concrete mould Y_00_10%	28	28	0	22MAY20	19JUN20	17:15
CON002	Concrete mould Y_00_20%	28	28	0	22MAY20	19JUN20	17:45
CON003	Concrete mould Y_00_30%	28	28	0	27MAY20	24JUN20	15:30
CON004	Concrete mould Y_00_40%	28	28	0	27MAY20	24JUN20	15:55
CON000	Concrete mould Y_00_Ref //	28	28	0	02JUN20	[illegible]	15:15
CON001	Concrete mould Y_00_10% //	28	28	0	26MAY20	23JUN20	15:20
CON002	Concrete mould Y_00_20% //	28	28	0	26MAY20	23JUN20	15:45
CON003	Concrete mould Y_00_30% //	28	28	0	29MAY20	26JUN20	16:45
CON004	Concrete mould Y_00_40% //	28	28	0	29MAY20	26JUN20	17:10

Table (3. 1): Time-line for testing Y_00 (Experimental Design schedule)

Subsequently, the same process was done for (Y_1), (Y_2) and (Y_3). *
The moulding process starts with adjusting the ratios of concrete ingredients according to the (EN) in conformity to (ASTM) standards. The used cement is CEM I 42.5 and standard CEN sand, and potable water that conforms to (EN 196-1) and (ISO 679). The mixture varies according to the replacement of concrete with stone sludge. Table (3.2) shows how the addition of stone sludge to cement may affect the rations for sample Y_00.

Specimens	Sand	Cement	Additive (stone sludge)	Water
Y_00_Ref	1350	450	0	225
Y_00_10%	1350	405	45	225
Y_00_20%	1350	360	90	225
Y_00_30%	1350	315	135	225
Y_00_40%	1350	270	180	225

Table (3. 2): Concrete mix (*Samples are subject to +- 5 gm; an acceptable variance)*

** Refer to Appendices (I), (II), (III), (IV) and (V)*

The ingredients are mixed in the mixer, switch at (1) according to the European standard (EN 196 T1) and (ISO R/679) – (ASTM C 305) – (BS 4550).

Then, the slump test (workability test) is applied to examine the flow of concrete after the addition of each percentage of stone sludge, according to (DIN EN 196-1:2016-11).
By measuring the diameter of the concrete flow in two perpendicular sides after inducing hammering pulses. It was observed an improvement in the rheological behaviour of cement mortar with stone sludge, which is ascribed to the grain size distribution of the sludge powder.

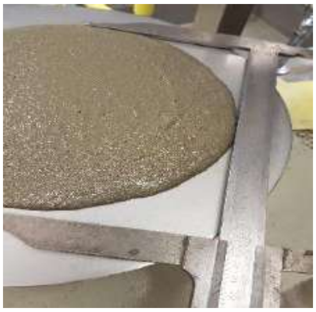


Figure (3. 4): Mixing

Top: Slump test
Bottom: Mixing machine

The protocol sheet for each sample should have the name, date and timing, the type of vibrator, the mould material (Metal), as well as all the ingredients weights, in addition to the measurement of the workability test. The moulded samples are then kept in the climate chamber at 20 °C and humidity of 65 %. They are kept for 24 hours inside an enclosed cabinet for protection, covered to ensure no moisture loses.

They are then de-moulded and placed in a water container to be tested after 7, 28 and 56 days.

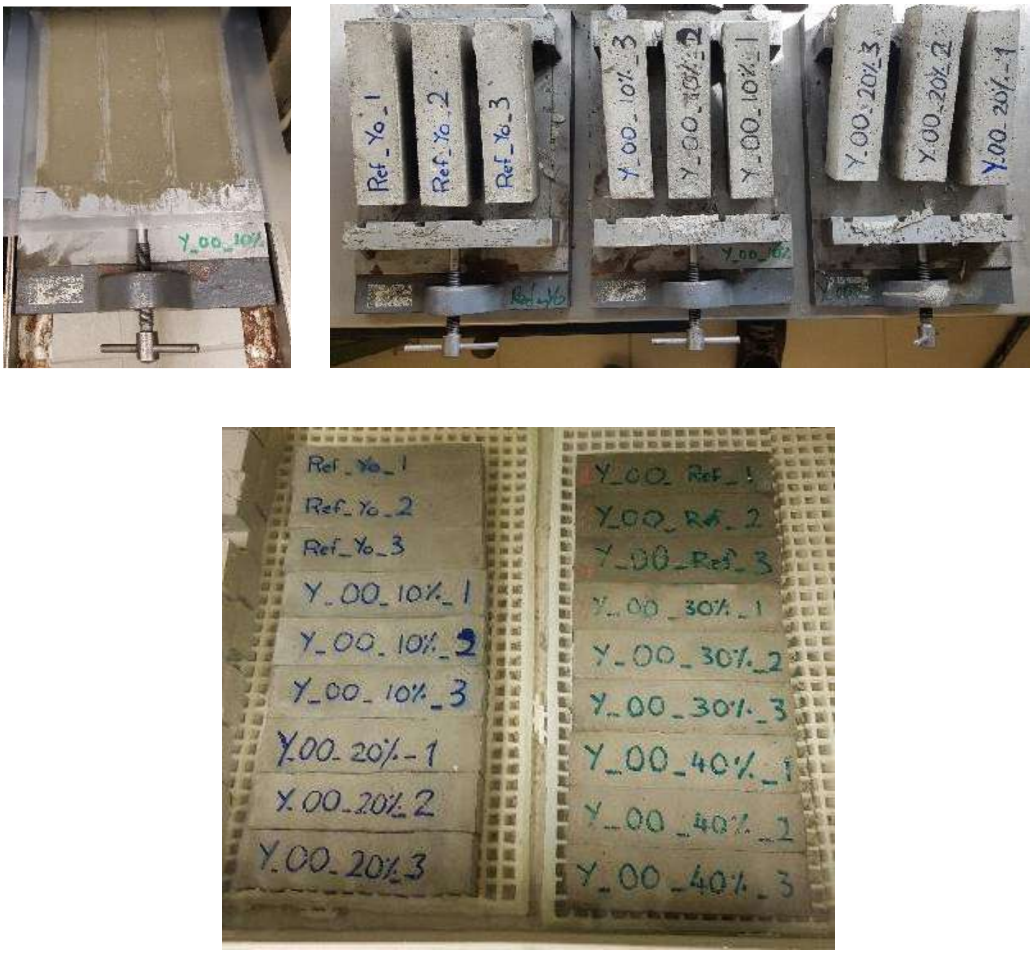


Figure (3. 5): Moulding

Top left: Moulding **Top right:** De-moulding

Bottom: Water sink

3.5. The physical behaviour test

3.5.1 Sieve analysis (Laser granulometry)

The physical characterization of the powder particles was observed using Laser diffraction granulometry. Technically, striking the particles with a laser beam and the measurements are taking according to the diffraction and scattering of the laser beam.

The chart below shows the fineness of the particle sizes according to the sieve passing percentages % by mass of the sieve residue.

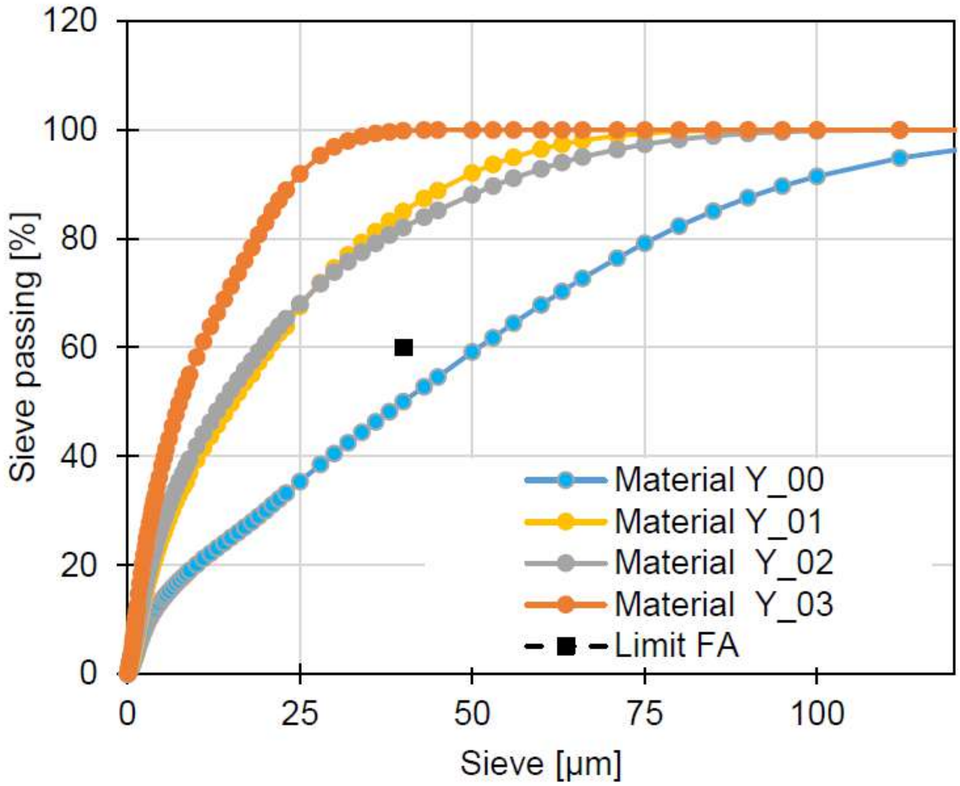


Figure (3. 6): Sieve analysis chart (Laser granulometry)

The physical requirements for cement additives is compared to the fineness of the fly ash, when sieving on a sieve with a mesh size of 0.45 mm.

For fly ash, the fineness must not exceed 40% by mass with a deviation factor of ± 10%, according to (EN 450-1:2012) (black dot refers to the fly ash limit).

The fineness may be determined by wet screening according to (EN 451-2) or by air-jet screening according to (EN 933-10) as tested.
All samples had to pass through a 0.45 mm (45-micrometre) sieve.
A 100 gm is weighed initially then sieving them on a rotor machine for 5 minutes, then weighing what stayed behind to analyze the particle size of each sample. It was observed that the sludge powder is of a very high Blaine fineness value.

The obtained results shows high fineness for stone sludge, which is able to cohere better in concrete mixtures. It is also worth mentioning that Fly ash with analogous conditions improved the rheological parameters of cement paste.

Specimens	Initial mass in gram	Retained mass in gram	Ratio
Y_0	10	2.87	28.7%
Y_1	10	1.12	11.2%
Y_2	10	1.51	15.1%
Y_3	10	1.28	12.8%

Table (3. 3): Sieve passing in grams

Figure (3. 7): Sieving machine

3.5.2 Chemical analysis

The chemical analysis was carried out four times per each specimen Y_00, Y_01, Y_02 and Y_03.

The table (3.4) shows the accumulative results of all four specimens. The examined material contains about 70% of amorphous silica or silicates (SiO_2), which is found in natural stones, about 10% of iron (III) oxide or ferric oxide with the formula (Fe_2O_3) known as rust, and about 3 % of calcium oxide (CaO) which is known as quicklime or burnt lime, which are all inorganic compounds.

Sample	Y_00 [M-%]	Y_01 [M-%]	Y_02 [M-%]	Y_03 [M-%]	International norms requirement	
Properties	**Result**	**Result**	**Result**	**Result**	**EN 197-1**	**ASTM C150**
(LOI)	1,88	3,15	3,1	3,02	TOC =< 0.2 %	< 3
SiO_2	76,84	72,14	72,41	72,56	> 25 %	
TiO_2	0,42	0,48	0,51	0,49		
Al_2O_3	2,11	2,31	2,52	2,48		< 6%
Fe_2O_3	10,14	11,53	11,27	11,29		< 6%
MnO	0,03	0,03	0,03	0,03		
MgO	0,95	1,06	1,09	1,08	< 5%	< 6%
CaO	2,17	3,18	3,10	3,03		
Na_2O	2,10	2,23	2,15	2,18		
K_2O	3,76	4,05	3,99	3,99		
P_2O_5	0,05	0,06	0,06	0,06		
SO_3	0,04	0,05	0,04	0,05	< 5 %	< 3 %
SrO	0,02	0,02	0,02	0,02		
Total	100,5	100,28	100,3	100,27		

CaO / SiO_2 > 2%

Table (3. 4): Chemical analysis

The level of sodium oxide (Na_2O) equivalent in % is determined by the formula
$Na2O + 0.658\ K_2o = 2.165+0.658(3.94) = 4.75$ (For Y_00)
While, the maximum value should be at least 0.60% + 0.10%, thus 0.70% for a CEM I. Whereas, the $CaCO_3$ content in % is determined by the formula
$CaCO_3 = 1.785 \times CaO = 1.785 \times 2.17 = 3.87$ (For Y_00)
Last but not least, $MgCO_3$ (dolomite) content in % is determined by the formula
$MgCO_3 = 2.092 \times MgO = 2.095 \times 0.95 = 1.99$ (For Y_00),
according to the methods in (DIN EN 196-2) and (DIN B 12-109).
Meanwhile, the **Loss on ignition (LOI)** test is done to investigate the change in weight after heating.

In conclusion, satisfactory results were obtained for the organic content. In addition, almost no presence of chlorides observed, which have a corrosive effect on concrete, nor sulphates that have a detrimental effect on concrete internally due to the formation of ettringite, which is an expansion component. (70), (71)

To study the chemical composition of all other constituents of stone sludge. The major processed types are the ornamental stone like **Marble and Granite**, then comes the **Natural stone** like (Cosentino, Sapienstone…) which contain organic substances. Thus, require a loss on ignition test to quantify organic substances in stones.
Ceramics, which the organic substances are considered a critical constituent in clay-based by-products such as ceramics. Meanwhile, binders like polymers or colloids and plasticizers are used in dry powder and plastic forming; in slurry processing, deflocculants, surfactants, and antifoaming agents to improve processing. Moreover, liquids are also added in plastic and slurry processing.
Porcelain, which is considered as a glazed or un-glazed vitreous ceramic-ware used primarily for technical purposes.
Artificial sintered stone slabs like (Lapitec, Silestone, Dekton…). (72)

Chemical composition	Marble	Granite
Lime (CaO)	38–42%	
Silicon Dioxide (Silica) (SiO_2)	20–25%	70.18%
Aluminum Oxide (Alumina) (Al_2O_3)	2–4%	14.47%
($MgCO_3$ and others)	30–32%	
Oxides (NaO and MgO)	1.5–2.5%	
Potassium Oxide (K_2O)		4.11%
Sodium Oxide (Na_2O)		3.48%
Calcium Oxide (CaO)		1.99%
Iron (II) Oxide (FeO)		1.78%
Iron (III) Oxide		1.57%
Magnesium Oxide (MgO)		0.88%
Water (H_2O)		0.84%
Titanium Dioxide (TiO_2)		0.39%
Diphosphorus Pentoxide (P_2O_5)		0.19%
Manganese Oxide (MnO)		0.12%

Table (3. 5): Chemical composition of marble and granite

The stone sludge powder's chemical analysis shows a major content of amorphous silica or silicates (SiO_2), with the loss on ignition (LOI) of about 2% and very small amount of sulphur trioxide (SO_3) of about 0.02%. On the contrary, marble shows a major content of lime (CaO) around 40%, with less amount of silicon dioxide (silica) (SiO_2) around 22%, and a very small values of aluminum oxide (alumina) (Al_2O_3) between 2 and 4%, CaO values of 0 to 6%, and traces of oxides like Na_2O and K_2O at a range of 1.5 to 2.5%. Granite shows a significant amount of silicon dioxide (silica) (SiO_2) around 70%, with less amount of aluminum oxide (alumina) (Al_2O_3) around 14%, and traces of oxides between 0 to 4%. It is worth mentioning that there is a remarkable amount of ferric oxide (Fe_2O_3), because of using gang saws during the cutting operations of granite. (73), (74), (75) Conclusively, based on Bogue equation: $C_3A = 2.6504\ Al_2O_3 - 1.6920\ Fe_2O_3$.

It was observed that, as the stone sludge powder increases the tricalcium aluminate (C_3A) content decreases. This is ascribed to the low amounts of aluminum oxide (Al_2O_3) and ferric oxide (Fe_2O_3) in stone sludge in comparison with plain cement. (ASTM C150)

3.5.3 Laser analysis

The table (3.6) shows the physical characteristics of the stone sludge grains for all samples collected. It shows the grain-size distribution of stone sludge particles, and significant fine-sized particles that have the ability to fill in voids among aggregates particles, resulting in higher density and lower porosity. The fineness of stone sludge decreased the porosity or the voids in the concrete matrix. As a result of its micro-filler ability, it enhanced the hydration process between cement grains, due to the low water penetration through the pores and capillaries. Moreover, the high surface area led in a higher water demand. The volume of stone sludge is recorded at about 1.1 cc (centimeter cube), and about 2.71 g/cc as specific gravity. *

Mess. No	Volume cc	Deviation cc	Density g/cc	Deviation g/cc
1	1.1041	-0.003	2.7239	0.0073
2	1.104	-0.0031	2.7242	0.0076
3	1.1061	-0.001	2.7192	0.0025
4	1.1065	-0.0006	2.7181	0.0015
5	1.1084	0.0013	2.7135	-0.0032
6	1.1074	0.0003	2.7159	-0.0007
7	1.1082	0.001	2.714	-0.0026
8	1.107	-0.0001	2.7169	0.0003
9	1.1093	0.0022	2.7112	-0.0054
10	1.1101	0.003	2.7093	-0.0074

** Refer to Appendix (VI)*

Table (3. 6): Sieve analysis of sample Y_00

3.5.4 Colour factor

From an architectural perspective, colour is a factor affecting the aesthetic aspects. Many designers tend to use fair-faced concrete in various applications. According to the chemical analysis of the samples collected in this research, it was concluded that there were high percentages of silicate, in addition to limestone (calcium carbonate) that influenced the brighter concrete and mortar colours. However, it depends on the scatter of materials processed (like oxides…) that might affect the colour as well.

3.6. Fresh concrete properties

Setting time (Soundness test)

The cement pastes were prepared by using laboratory type mixer at switch (6) according to (EN 196 T3). Five pastes were mixed at substitution percentages of cement by stone sludge at percentages 0, 10, 20, 30 and 40%, as in table (3.7). All the mixes had a net weight of 500 gm. Water amount was added till the paste reached the standard consistency. The initial and final setting times of the cement pastes were determined in the table (3.8). Vicat apparatus was used to determine the penetration of a one (mm) square section needle in the Vicat's mould 5 to 7 mm from the bottom of the mould, according to (EN 196-3).

Figure (3. 8): Vicat apparatus

Cement paste mixes in (%)	Cement addition in (gm)	Stone sludge in (gm)	Net weight in (gm)	Water in (ml)	Drop in (mm)	Time
0	410	90	500	132	6	10:05
10	365	135	500	133	7	10:30
20	320	180	500	132	5	10:40
30	275	225	500	132	7	10:45
40	230	270	500	142	8	10:50

Table (3. 7): Cement paste mixtures

The initial setting time should be more than 45 minutes and the final setting time should not exceed 10 hours (600 minutes), according to (EN 196-3).

Cement paste mixes in %	Initial time	Setting time
0	12:00	13:00
10	12:40	13:20
20	13:05	14:10
30	13:10	14:20
40	13:40	14:30

Table (3. 8): The initial and final setting times of the cement pastes

The specific gravity of cement was investigated using Le Chatelier flask. In addition, the soundness of cement pastes was determined by Le Chatelier method. The values obtained from the expansion length of the indicator arms of the split cylinder at a curing age of 24 hours, in addition to those after subjecting the specimens to heat for three hours were recorded as in table (3.9).

Cement paste mixes in (%)	Measurements in (mm)	Measurement in (mm) after 3 hours of heating	Length difference
0	40	40.5	0.5
10	22	22.5	0.5
20	27	27	0
30	27.8	27.5	0
40	18	18	0

Table (3. 9): The obtained measurements of Le Chatelier flask

Figure (3. 9): Le Chatelier flask

The obtained results show that the addition of stone sludge as a replacement with cement at percentages up to 40% does not affect the concrete and mortar mixtures adversely.

It is observed that the length difference of the split cylinder indicator arms is almost zero. Thus, the volume expansion rate of concrete after hardening is not affected significantly, consequently enhancing the durability of concrete.

3.7. The mechanical behaviour test

Specimens of mortar are stored in water. On the 7^{th} day, 28^{th} day, eventually on the 56^{th} day they were dried, measured 40*40*160 mm and weighed in preparation to be tested, according to (DIN EN 196-1).

3.7.1. Flexural strength

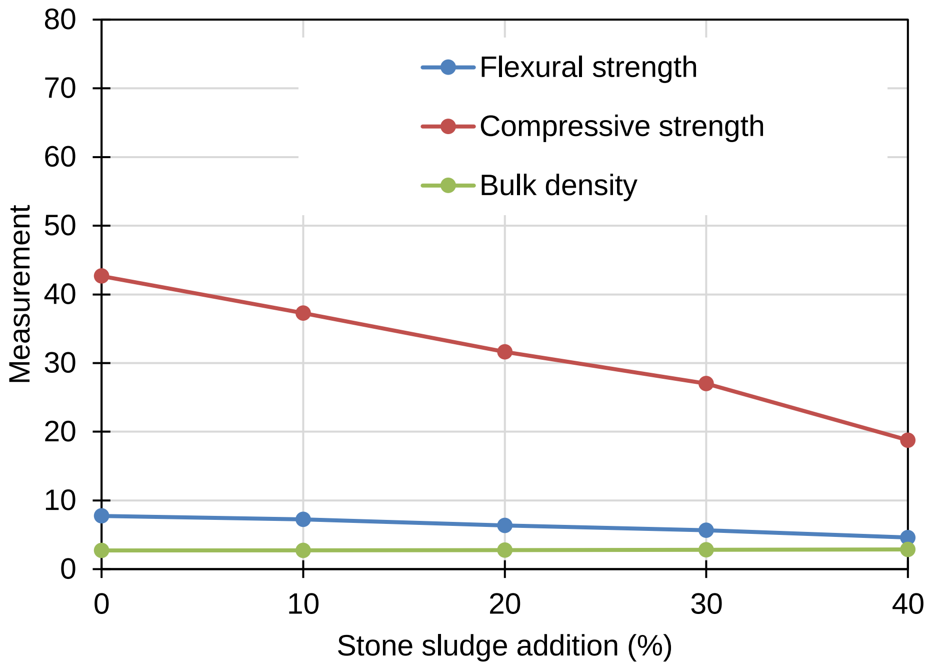
Three-point bending test is applied to all 3 mortar moulds of each sample at curing ages of 7, 28, 56 days. In order to investigate the flexural strength of all specimens with different replacement percentages of stone sludge with concrete at 10, 20, 30 and 40%. The reference specimen with pure Portland cement without any additives nor replacement was used to compare between the obtained results. Pressure is applied on the centre of the specimen until it cracks and splits into 2 halves. During the test, the pressure is applied at a slow pace, in order not to induce a dynamic behaviour to the material that might induce an inertia affecting the results. The compression strength test measurements of concrete were performed at 7, 28 and 56 days of curing age.

Tables (3.10) and (3.11) show the test results for Y_00 at 7 and 28 days respectively. It recapitulates that 10 % replacement of cement with stone sludge caused a consequent decrease of about 10 % in compressive strength and in such manner with the increase in the replacement rates.

Figure (3. 10): Bending test

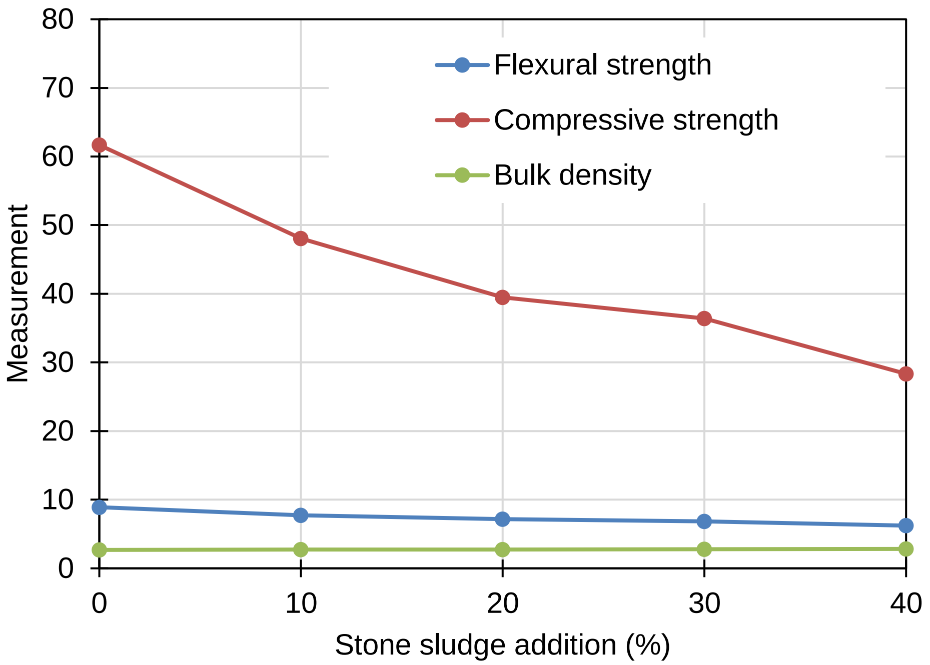
Average (7 days)	Stone sludge addition in %	Flexural strength	Compressive strength	Bulk density
Y_00_Ref	0	7.739	42.66	2.74
Y_00_10%	10	7.246	37.25	2.74
Y_00_20%	20	6.338	31.65	2.76
Y_00_30%	30	5.671	27.02	2.83
Y_00_40%	40	4.605	18.78	2.87

Table (3. 10): Flexural, Compressive strengths and Bulk density of Y_00 at 7d



Average (28 days)	Stone sludge addition in %	Flexural strength	Compressive strength	Bulk density
Y_00_Ref	0	8.905	61.68	2.68
Y_00_10%	10	7.740	48.07	2.75
Y_00_20%	20	7.155	39.46	2.75
Y_00_30%	30	6.839	36.39	2.77
Y_00_40%	40	6.224	28.34	2.83

Table (3. 11): Flexural, Compressive strengths and Bulk density of Y_00 at 28d



The three-point bending test results show a consequent decrease in the flexural strength as the replacement amount of cement with stone sludge increased.
It was observed a strong correlation between the flexural and compression strength. Thus, there is a direct proportion decrease or increase in both strengths in accordance with the stone sludge addition, as shown in the relative tables (3.12) and (3.13).
The obtained results were compared with the European standard (DIN EN 197-1:2011-11) for cement II 42.5 N, that requires a strength of >42.5 MPa on the 28th day.
In order to better evaluate the behaviour of mortar after replacing stone sludge with cement sand in the mortar, comparisons were carried out on Fly ash, which is widely used as a concrete additive, according to (DIN EN 450-1).

3.7.2. Compression strength test

After the three-point bending test, the mortar specimens are split into halves, which gives a double prisms for each sample; the test is applied to all 6 halves of each sample. The internal cracks throughout the mortar prism, along the direction of the compression load could be investigated. The concrete tends to buckle or expand laterally, and the prism fails leaving two truncated pyramids one over the other in a concave shape. (Poisson's effect)

Figure (3. 11): Compression test

Left: Compression test **Right:** Specimen after test

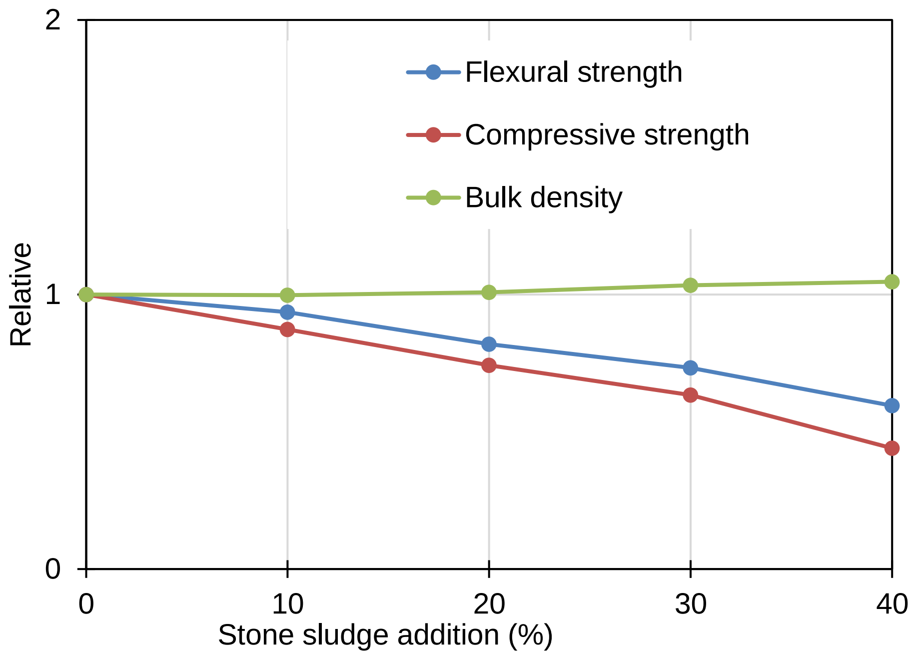
The protocol sheets for both tests should have the name, date and timing of the specimen moulding and during the test, the size, density and the measurement of the workability test. Consequently, the results were filled for the compression and bending tests. In tables (3.10) and (3.11) the results of the compression strength of each specimen at replacement percentages of stone sludge with concrete at the different curing ages were recorded. The results show a significant decrease in the results inversely proportional to the percentage of the additives in each specimen. Therefore, the more inert additives to active concrete the less test results it gets.*

The obtained results were compared with the European standard (DIN EN 197-1:2011-11) for cement II 42.5 N, that requires a strength of >42.5 MPa on the 28th day.

** Refer to Appendices (I), (II), (III) and (IV)*

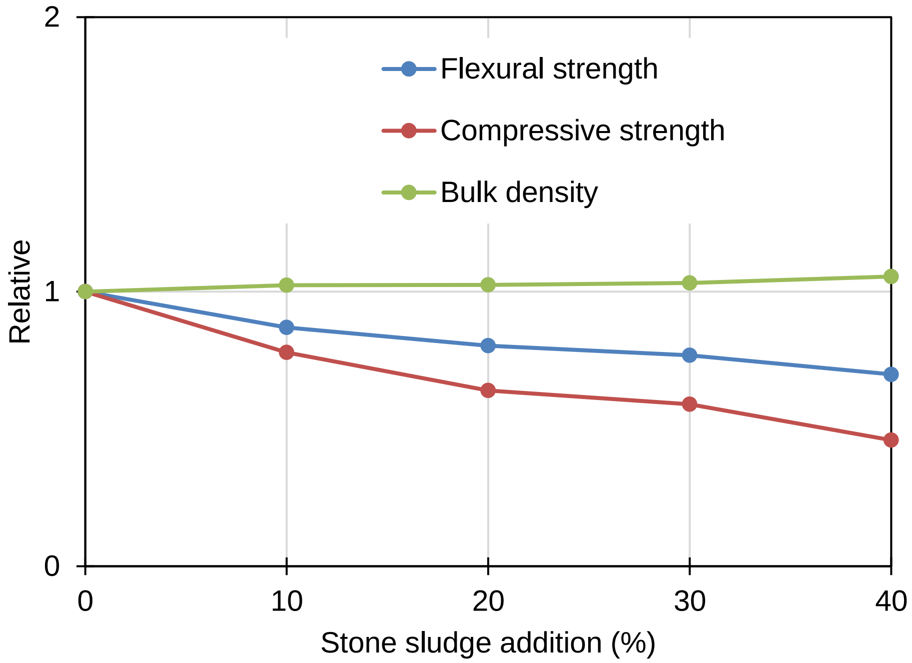
Relative (7 days)	Stone sludge addition in %	Flexural strength	Compressive strength	Bulk density
Y_00_Ref	0	1.000	1.00	1.00
Y_00_10%	10	0.936	0.87	1.00
Y_00_20%	20	0.819	0.74	1.01
Y_00_30%	30	0.733	0.63	1.03
Y_00_40%	40	0.595	0.44	1.05

Table (3. 12): Flexural, Compressive strengths and Bulk density of Y_00 at 7d (Relative)



Relative (28 days)	Stone sludge addition in %	Flexural strength	Compressive strength	Bulk density
Y_00_Ref	0	1.000	1.00	1.00
Y_00_10%	10	0.869	0.78	1.02
Y_00_20%	20	0.804	0.64	1.02
Y_00_30%	30	0.768	0.59	1.03
Y_00_40%	40	0.699	0.46	1.06

Table (3. 13): Flexural, Compressive strengths and Bulk density of Y_00 at 28d (Relative)



The relative compressive strength results which is the quotient of the mean of the 6 obtained values of the compression strength of each specimen at different replacement percentages and the reference sample with pure portland cement without additives nor replacement, at the same different curing ages.
The charts represent the values of the relative strengths at different stone sludge replacement percentages with cement, whereas the blue line indicates the flexural strength behaviour, the red line indicates the compressive strength behaviour and the green line indicates the bulk density trend. The reference was assigned at 1 to all specimens at different ages. At a 10% replacement of stone sludge with cement, there is a relative decrease in the strengths and slightly the same manner as the replacement rates increase along with curing age.
It can be concluded that the influence of stone sludge replacement has an inversely proportional effect on the strengths of mortar, the deviation in the strength increases with the replacement percentages of stone sludge with cement. The reduction in the strengths of concrete is ascribed to the replacement of stone sludge which is an inert material with cement which is an active material. Thus, a dilution of pozzolanic reaction, as a result of a reduction in the cementitious materials.

3.7.3. Bulk density (Specific gravity) (Unit weight)

The results in the tables (3.12) and (3.13) reveal that the replacement of cement with stone sludge at 10% and 20% led to the increase in the bulk density by 1.02%, while at 30% and 40% it increased by 1.06%. The calculated average density was recorded at around 2.75 grams per centimetre cube, agreeing with the average density of the laser analysis. The obtained results show the behaviour of stone sludge particles to fill in the voids among the aggregate particles, increasing the bulk density.

3.7.4. The coefficient of variation (CoV)

The coefficient of variation values of compressive strengths of all specimens were calculated in the table (3.14) below for specimen Y_00 at all replacement rates. It is significant that the coefficients of variation for concrete with stone sludge replacement are approximately hovering over the same percentages in comparison to the reference concrete specimens at all curing ages. Though, it is not following a specific trend. Therefore, the effect of stone sludge replacement with cement can not be generalized.

Specimen	Test age	Compressive strength CoV in %
Y_00_Ref	28	1.90
Y_00_10%	28	1.43
Y_00_20%	28	1.58
Y_00_30%	28	3.74
Y_00_40%	28	2.78
Y_00_Ref	7	2.30
Y_00_10%	7	2.77
Y_00_20%	7	1.64
Y_00_30%	7	1.55
Y_00_40%	7	2.55

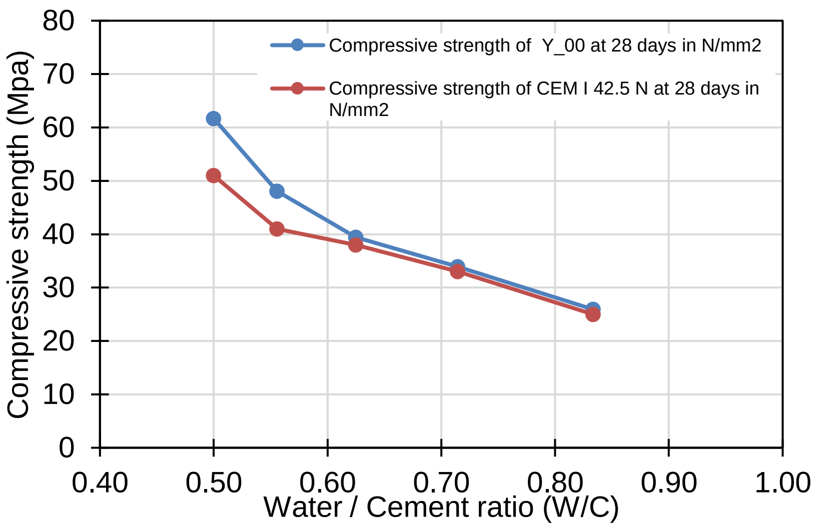
Table (3. 14): The coefficients of variation (CoV) of Y_00

3.7.5. Water to cement ratio (W/C)

In order to compromise the mechanical strength losses, water to cement ratio can be re-adjusted to give better results. It is observed in the table (3.15) that lower W/C ratios gives higher strength results for mortar and concrete specimens. Besides, excess water in the mixture causes the segregation of the sand and aggregates from the cement paste, in addition to the porosity because the excess water doesn't react.

Specimen	Sand in (gm)	Cement in (gm)	Stone sludge in (gm)	Water in (Liters)	W/C	Compressive strength of Y_00 at 28d in (Mpa)	Compressive strength of CEM I 42.5 N at 28d in (Mpa)
Y_00_Ref	1350	450	0	225	0.50	61.68	51
Y_00_10%	1350	405	45	225	0.56	48.07	41
Y_00_20%	1350	360	90	225	0.63	39.46	38
Y_00_30%	1350	315	135	225	0.71	33.91	33
Y_00_40%	1350	270	180	225	0.8	25.92	25

Table (3. 15): Water / Cement ratio of Y_00



The results are compared with the obtained strengths for CEM I 42.5 N at 28 days, according to the (Cement leaflet Concrete technology B 20 2.2017).

3.8. Comparative analysis

There is a linear relationship between the compressive and tensile strengths of concrete mixtures.
The compressive strengths of cement mortar Y_00, when replacing the stone sludge waste powder with cement at percentages of 0% (control reference), 10, 20, 30 and 40% by weight, at a curing age of 7 days, were 42.66, 37.25, 31.65, 27.02 and 18.78 Mpa respectively. However, the strengths at a curing age of 28 days were higher than the latter strengths with the same manner, as 61.68, 48.07, 39.46, 36.39 and 28.34 Mpa respectively. Whereas the strengths obtained at a curing age of 56 days, with replacement rates 20 and 40% by weight were higher as 45.72 and 30.02 Mpa respectively.

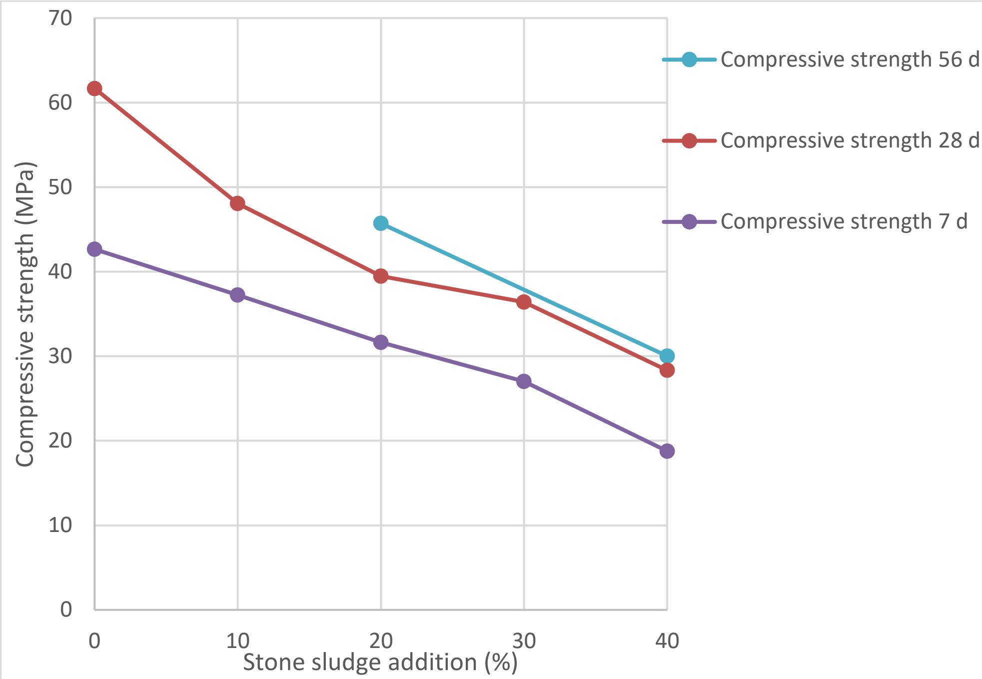
Consequently, the relative compressive strengths of cement mortar Y_00 have changed considerably, when replacing the marble waste powder with cement at percentages of 0% (control reference), 10, 20, 30 and 40% by weight. At a curing age of 7 days, it ranged from 1 to 0.44 respectively. At the age of 28 days, it ranged from 1 to 0.46 respectively. Moreover, at the age of 56 days, it ranged from 1 to 0.49 respectively.

On the other hand, the flexural strengths at a curing age of 7 days were 7.739, 7.246, 6.338, 5.671 and 4.605 Mpa respectively. However, the strengths at a curing age of 28 days were 8.90, 7.74, 7.15, 6.83 and 6.22 Mpa respectively. Whereas, the strengths obtained at a curing age of 56 days, with replacement rates 20 and 40% by weight were higher as 7.76 and 6.36 Mpa respectively.
Consequently, the relative flexural strengths at a curing age of 7 days, ranged from 1 to 0.59 respectively. At the age of 28 days, it ranged from 1 to 0.69 respectively. Moreover, at the age of 56 days, it ranged from 1 to 0.71 respectively.

Based on the results of the 7th, 28th and 56th day of the compressive strength, it is considerable that there is a significant loss in strengths, as a result of replacing the cement content in the mixture with stone sludge, as in table (3.16).

In table (3.17), it shows the declining trend for most of the relevant researches replacing marble waste powder with cement, which is almost the same for all of them. The scattering diagram shows the inextricable correlation between the compressive and tensile strengths. Meanwhile, the replacement of marble waste powder with aggregates exhibit a different behaviour.

In table (3.18), it shows the effect of limestone (LS) replacement in comparison to marble waste (MW) and recycled aggregates (RA). It could be concluded that the effect of limestone as cement replacement shows a better behaviour in the concrete properties in comparison to the recycled aggregates and marble waste powder.



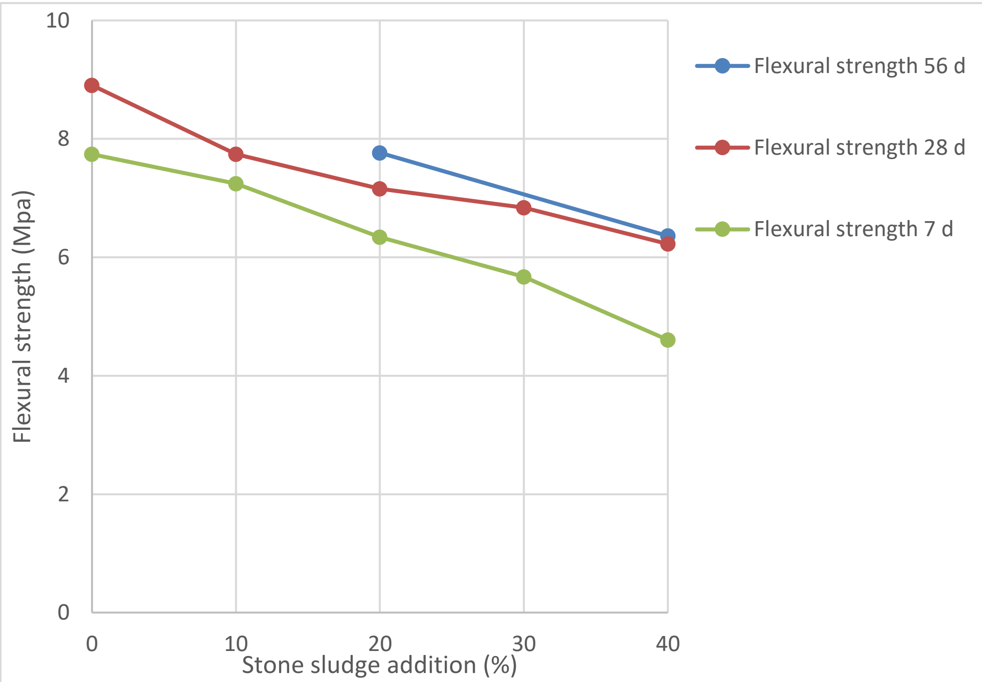
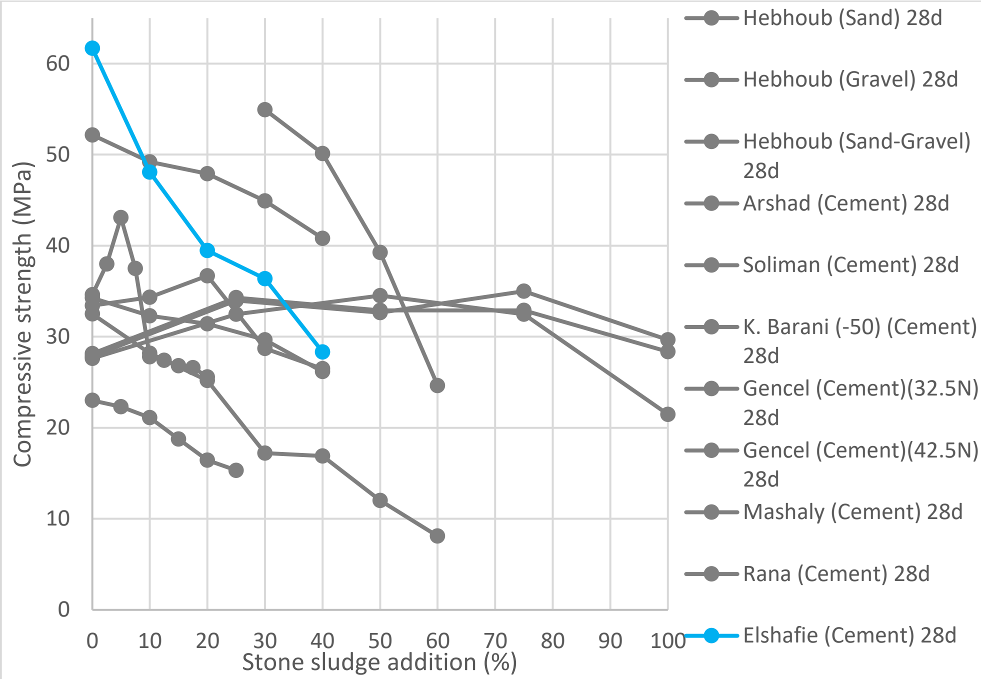


Table (3. 16): Comparison of the strengths obtained of Y_00



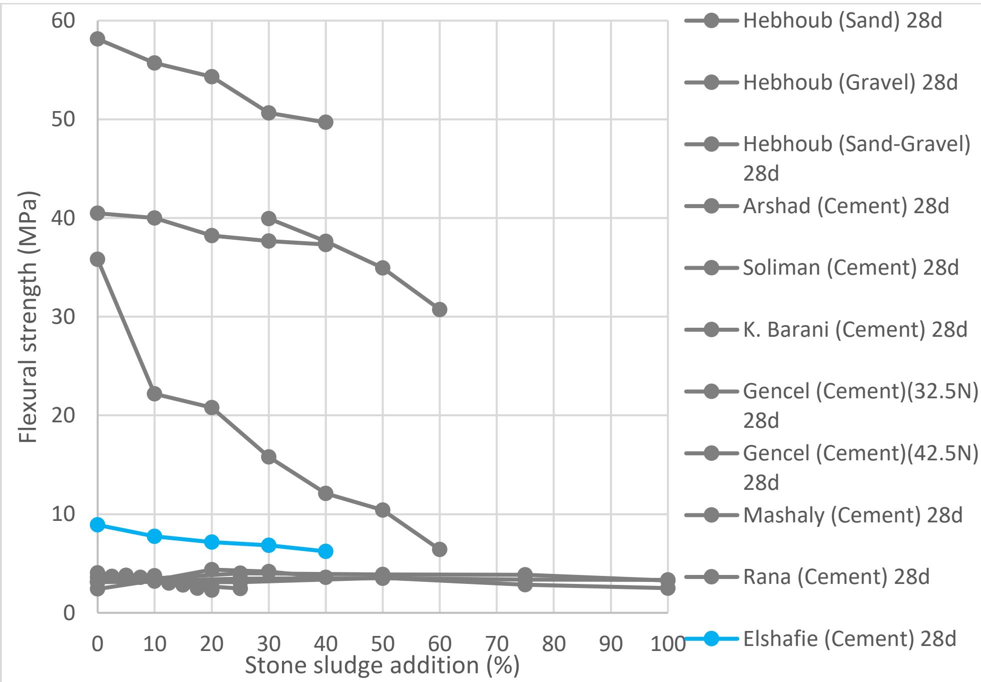
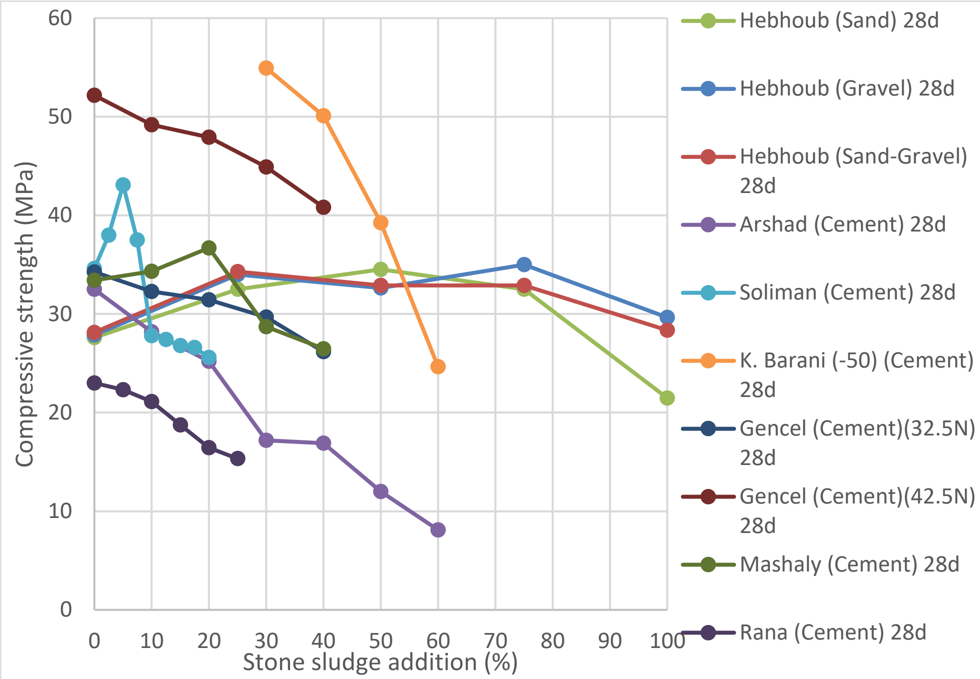


Table (3. 17): Comparison of the strengths obtained in relevant researches



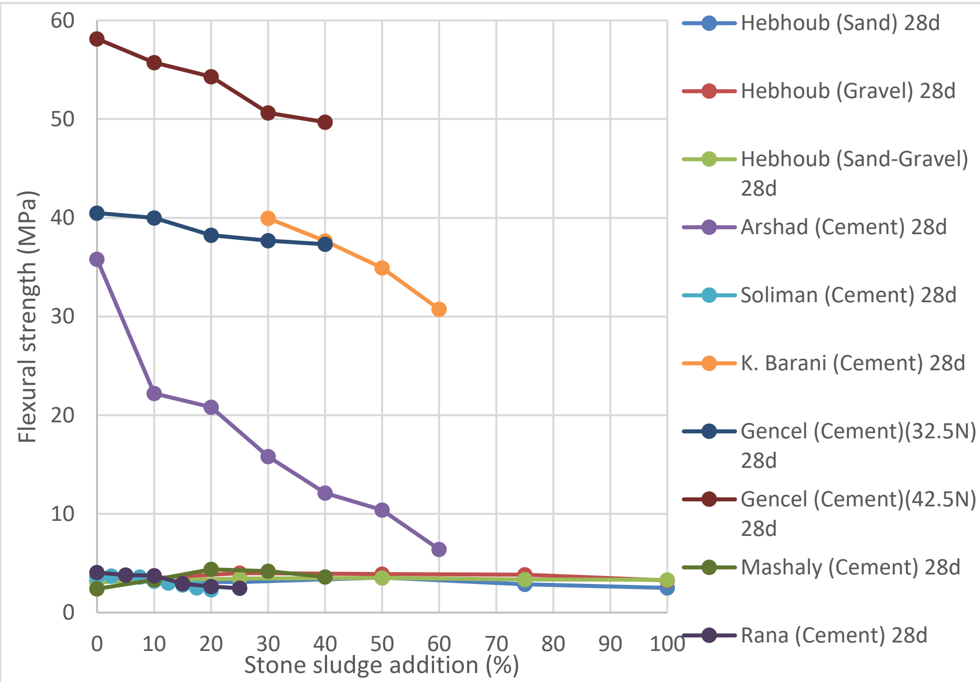
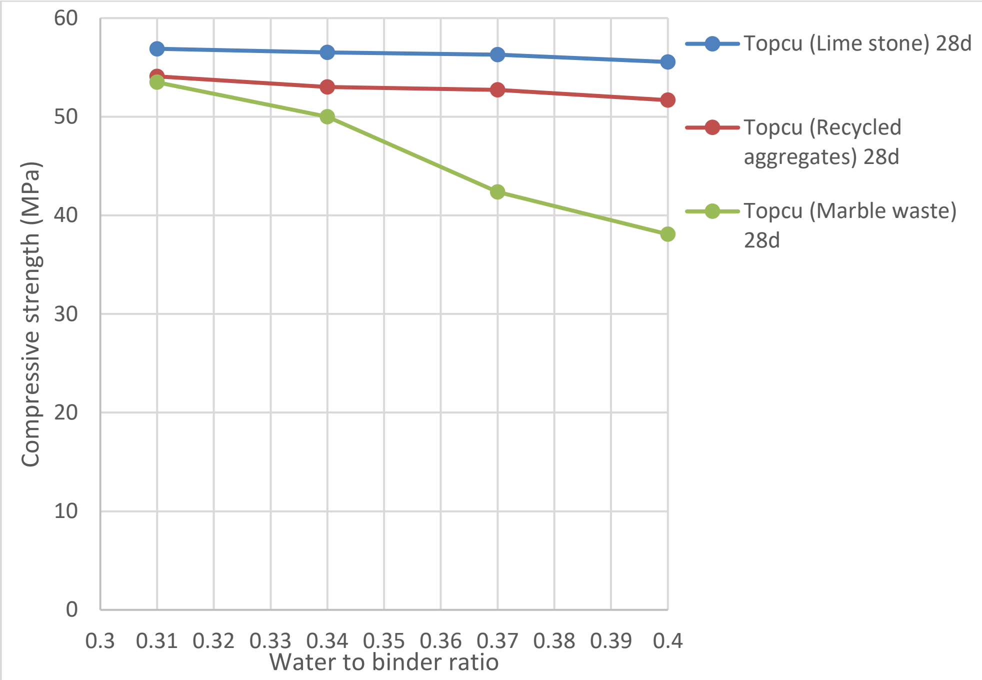


Table (3.17): Comparison of the strengths obtained in relevant researches



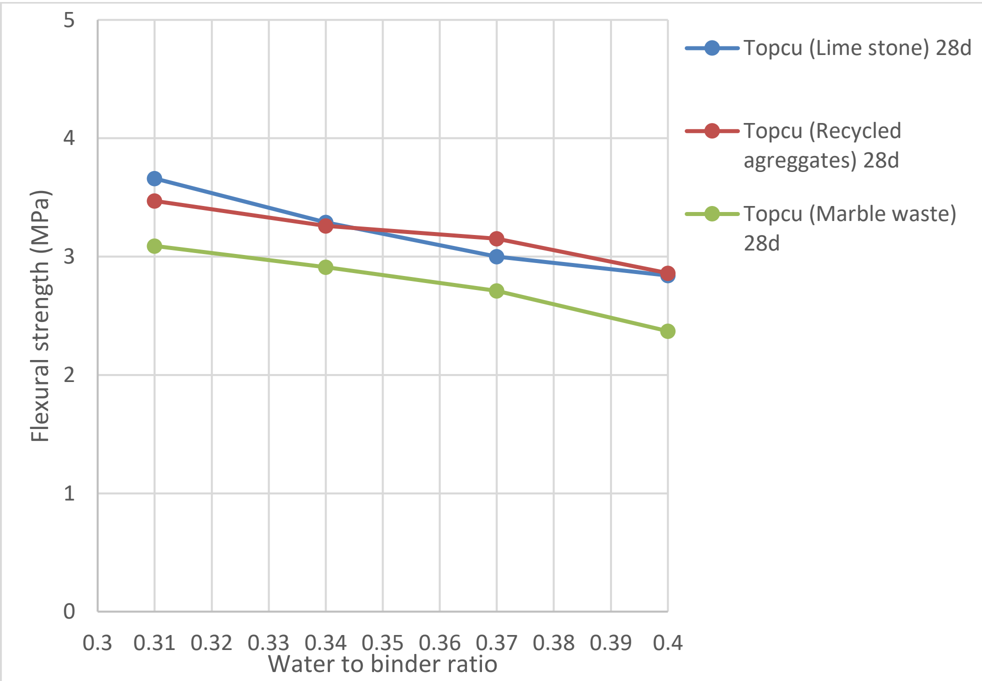


Table (3. 18): Comparison of the strengths obtained with limestone (LS), recycled aggregates (RA) and marble waste powder (MW) when replaced with cement

The replacement of cement or fine aggregate with stone sludge powder with replacement rates, has an effect upon the cement paste as well on the characteristics of hardened concrete mixes. It can be observed from the obtained results that both the compressive and tensile strengths of concrete follows the same trend whether with an increase or a decrease with the replacement rates of stone sludge powder.

The linear equation according to (Aliabdo, 2014) represents the relationship between the compressive strength (f_c) and the splitting tensile strength (f_t) of concrete mixtures when replacing stone sludge powder with cement (a) and with fine aggregate (b) respectively.

$f_t = 0.054\ f_c + 1.725 \quad R^2 = 0.761$ (a) Partial replacement of cement

$f_t = 0.069\ f_c + 1.045 \quad R^2 = 0.864$ (b) Partial replacement of sand

The steel–concrete bond strength (f_b) could be derived accordingly from the following linear equation when replacing stone sludge powder with cement (a) and with fine aggregate (b) respectively.

$f_b = 0.082\ f_c + 5.506 \quad R^2 = 0.644$ (a) Partial replacement of cement

$f_b = 0.095\ f_c + 5.269 \quad R^2 = 0.625$ (b) Partial replacement of sand

The ultrasonic pulse velocity (UPV) could be derived accordingly from the following linear equation when replacing stone sludge powder with cement (a) and with fine aggregate (b) respectively.

$V = 2.984\ f_c^{0.117} \quad R^2 = 0.852$ (a) Partial replacement of cement

$V = 3.414\ f_c^{\ 0.081} \quad R^2 = 0{:}840$ (b) Partial replacement of sand

The porosity (P) could be derived accordingly from the following linear equation when replacing stone sludge powder with cement (a) and with fine aggregate (b) respectively.

$P = -0.003\ f_c + 0.226 \quad R^2 = 0.776$ (a) Partial replacement of cement

$P = 0.093\ e^{-0.04\ fc} \quad R^2 = 0.953$ (b) Partial replacement of sand

It is clear that the fine stone sludge powder acts as a micro-fine filler; which fills in the voids and pores, consequently enhancing the cement matrix and interfacial transition zone (ITZ) properties, especially when replaced with fine aggregates (sand).

In case of replacing the fine aggregate with fine stone sludge powder, an enhancement in both compressive and tensile strengths is expected referring to the low porosity and good cement matrix obtained.

In case of replacing cement with fine stone sludge powder, the relatively decreased strengths could be compensated by adjusting the water to binder ratios. However, the excess amount of water in the mixture could also cause a decrease in the tensile strength, due to the reduction of the adherence between the interfacial transition zone (ITZ) of aggregate and the hydrated cement matrix.

Moreover, the flaky shape of the stone sludge powder plays a role in affecting the properties of concrete. The high fineness of stone sludge particles require more water for lubrication, to maintain the workability or the plasticity of cement paste.

3.9. Durability tests of concrete

The physical properties of concrete when replacing cement with stone sludge at percentages 10, 20, 30 and 40% were studied with regards to the permeable pore spaces (voids), rate of absorption (sorptivity), abrasion resistance and freeze and thaw resistance at curing age of 28 days, to identify the effects on each one of them.

3.9.1. The freeze and thaw test

CIF-Test: Capillary suction, internal damage and freeze-thaw test (CIF)

In this test, the improvement in the physical weathering properties of concrete due to the regional climatic changes that cause expansion and shrinkage is investigated.

The ingredients of concrete were quantified as in the table (3.19), according to the code (RILEM TC 176-IDC) that was based upon the former code recommendation of the CDF-test (Capillary Suction, De-icing agent and Freeze-thaw Test), according to (prEN-ISO 2736/2).

During the mixing process, the aggregates were added coarse first then finer respectively. The aggregates were mixed with doses of water and left for a minute to saturate. Consequently, the cement with 20% stone sludge replacement by weight was mixed for a couple of minutes with the last dose of water. It is worth mentioning that, during the mixing process the concrete mixture hardened, due to the increase in the water demand because of the stone sludge addition. Thus, an addition of a 47 gm superplasticizer enhanced the rheological behaviour of the cement paste.

Cement CEM I 42.5N	**Stone sludge 20 in (%)**	**Aggregates in (kg)**				**Water in (Litre)**	**Superplasticizer admixture in (gm)**
		0/2	2/4	4/8	8/16		
7.24	1.81	16.0	10.6	10.7	16.0	4.53	47
		53.3					

Table (3. 19): Ingredients ratios of the concrete mix of freeze and thaw test

Figure (3. 12): Mixing the concrete to produce concrete blocks

The freeze and thaw resistance test is performed by investigating the resistance of concrete against the alternation of temperature that leads to a change in the concrete properties. During the test, the reference temperature recording is measured at a reference point on the test surface (facing the PTFE plate) of the concrete specimen. Furthermore, the specimen is submerged in the test liquid (97% demineralized or distilled water and 3% NaCl) as a coupling medium, allowing the ultrasonic pulse wave to transfer between the transmitter and receiver transducers across the specimen. The transit time of the ultrasonic pulse wave that travels between the transmitter and receiver along the transit path or axis is recorded. As a result of the ultrasonic pulse wave, the reduction in the dynamic modulus of elasticity (E_{Dyn}) is recorded.

Special mould were used with a PTFE plate on one side (test surface), as in figure (3.13). After de-moulding the concrete blocks, they were kept in the damp storage room, to keep the moisture content of specimens for 24 hours. Subsequently, the specimens are kept in a water sink for 6 days, and then taken out and stored in the climate chamber at 20 °C and humidity of 65 %.

The test procedures:

Firstly, the dry-storage, which follows the afore-mentioned procedure. The specimens were kept in the climatic chamber for surface drying. On the 58th day, they were cut to the standard test dimensions 150 x 150 x 70 mm.

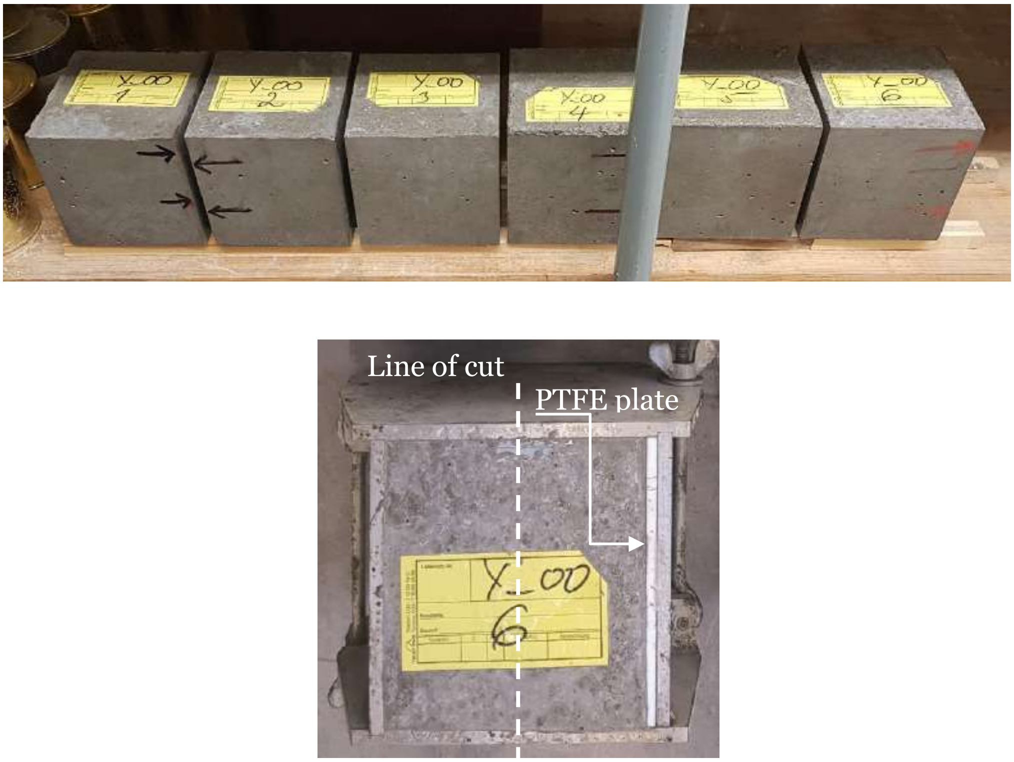


Figure (3. 13): Concrete blocks cutting

Secondly, the pre-saturation, preparation and sealing of the specimens: before and after sealing, the specimens were weighed, in order to calibrate them with the reference mass, to determine the moisture loss. It is worth mentioning that the lateral surfaces of the specimens, three days before the test, were treated adequately with an Epoxy resin that is durable at temperatures of -20 °C.

Figure (3. 14): Applying Epoxy resin

After sealing the specimens, they were placed in test container for 7 days on a spacer 5 mm high, with the test surface facing the bottom side of the container. Subsequently, the container was filled with the test liquid until it reached 10 mm without wetting the specimen's top surface. The test liquid's level was checked regularly every 3 days.

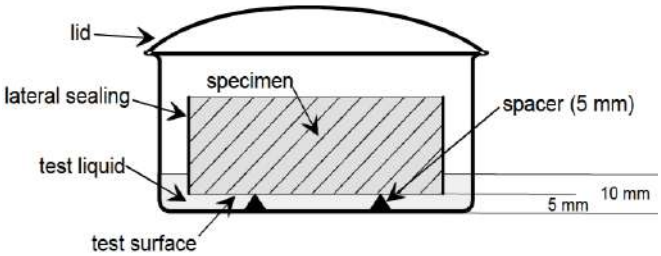


Figure (3. 15): Capillary suction

Finally, the freeze and thaw test which is a cyclic temperature attack to the specimens. During the freeze and thaw cycles, the specimens were placed in the test containers that were immersed 15 mm in the tempering bath inside the temperature-controlled chest.

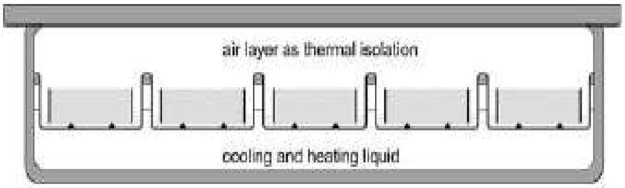


Figure (3. 16): Temperature controlled chest

The cyclic attack starts from + 20 °C, then with a constant cooling rate of 10 K/h, it reaches -20 °C in 4 hours. The temperature remains constant at -20 °C for 3 hours, then cycles back to the +20 °C with a constant heating rate of 10 K/h, and it remains constant for 1 hour at +20 °C. It is worth mentioning that the damage is measured when the temperature is above +15 °C.

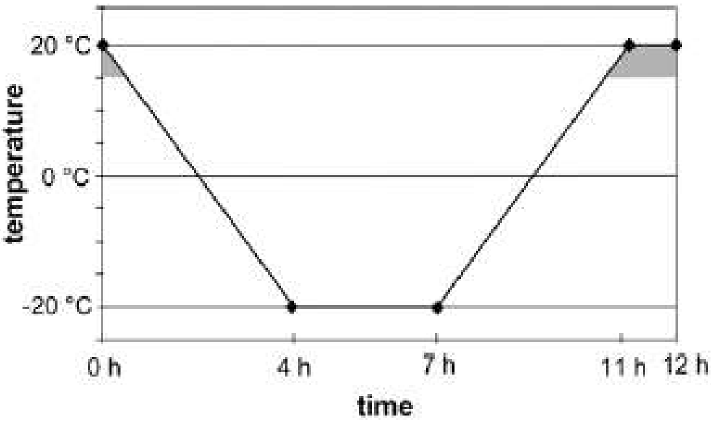


Figure (3. 17): Temperature cycle

Subsequently, the test containers were taken out from the temperature-controlled chest to be immersed in an ultrasonic bath for 3 minutes, in order to shake loose scaled material off the test surface. Then, by subtracting the mass of empty dried filter (μ_f) from the filter containing the dried scaled material (μ_b), the scaled material (μ_s) mass is calculated using equation $\mu_s = \mu_b - \mu_f$.

The total mass of scaled material (m_n) was measured using equation $m_n = \frac{\Sigma \mu s}{Area}$.

Figure (3. 18): Ultrasonic bath

The moisture uptake was measured by subtracting the masses divided by the reference mass, using equation $\Delta W_n = \frac{Wn - W1 + \sum \mu s}{W\ Ref}$ x 100.

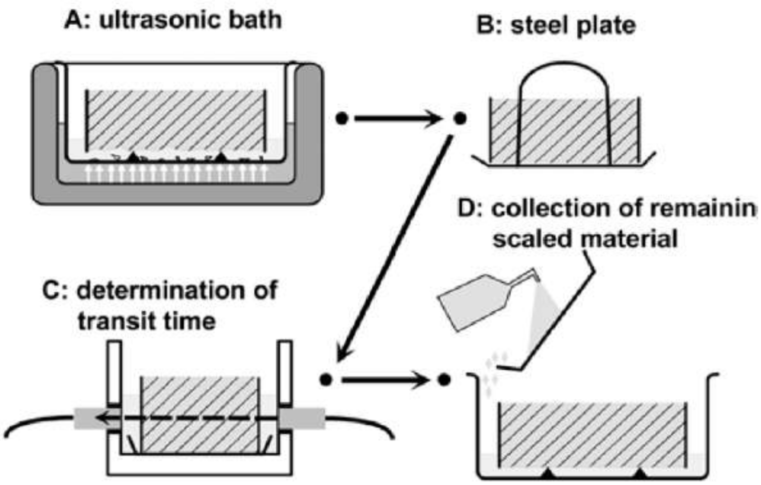


Figure (3. 19): Specimens handling

Ultimately, the internal damage was investigated by measuring the ultrasonic transit time passing along two perpendicular transit axes 35 mm from the test surface across the coupling medium (test liquid), which is reaching 10 mm above the transducers. The transit time (t_c) is calculated by dividing the transit length (l_c) by the velocity of the ultrasonic signal in the coupling medium (v_c), using equation $t_c = \frac{lc}{vc}$.

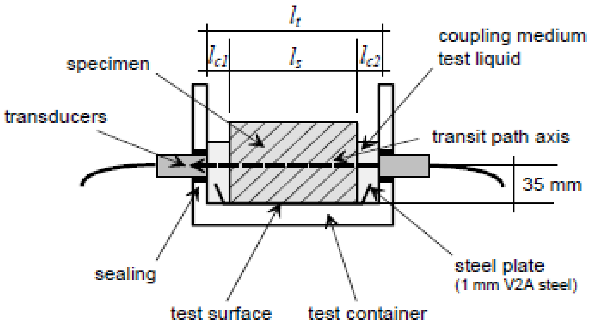


Figure (3. 20): Ultrasonic transit time measurement

The transit time across each specimen was recorded, as in table (3.20).

Transit time measurement in (μs)												
Cyclic attacks	**Specimen 1**		**Specimen 2**		**Specimen 3**		**Specimen 4**		**Specimen 5**		**Specimen 6**	
	Axis a-a	Axis b-b	Axis a-a	Axis b-b	Axis a-a	Axis b-b	Axis a-a	Axis b-b	Axis a-a	Axis b-b	Axis a-a	Axis b-b
0	42.1	44.1	41.8	42.2	42.1	42.4	40.6	42.1	42.2	41.8	41.4	42.2
8	42.4	44.7	41.9	42.4	42.4	42.7	41.1	42.4	42.6	42.2	41.7	42.6
12	42.3	44.5	42.1	42.4	42.4	42.6	41.2	42.4	42.7	42.2	41.7	42.7

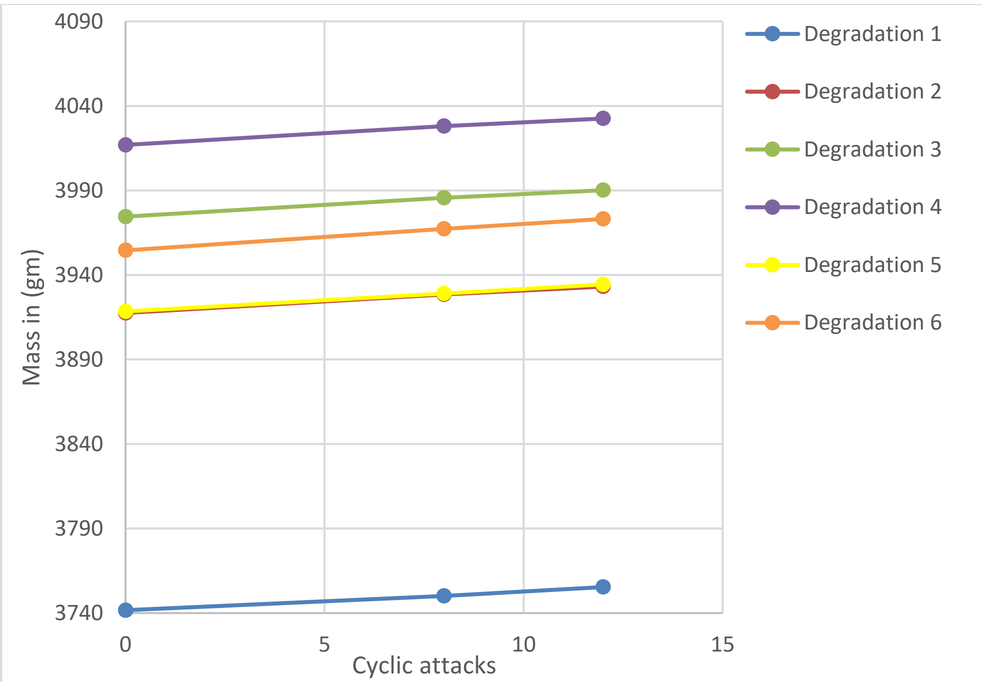
Table (3. 20): Transit time measurement

A sequence of measurements were taken at the start of the freeze and thaw cycle, and after the eighth cycle and the twelfth cycle. The measurements include the surface scaling, moisture uptake and the internal damage with regards to the ultrasonic transit time.

According to table (3.21), it was observed that as the cyclic attacks increase the water degree of saturation increased, due to the sucking action during the thawing process, consecutively increasing the mass of the specimens.

The mass of specimen (w_n) in (gm)						
Cyclic attacks	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Specimen 4**	**Specimen 5**	**Specimen 6**
0	3741.7	3917.5	3974.5	4016.9	3918.4	3954.5
8	3750.2	3928.4	3985.7	4028.0	3929.1	3967.2
12	3755.4	3933.1	3990.1	4032.5	3934.4	3973.1

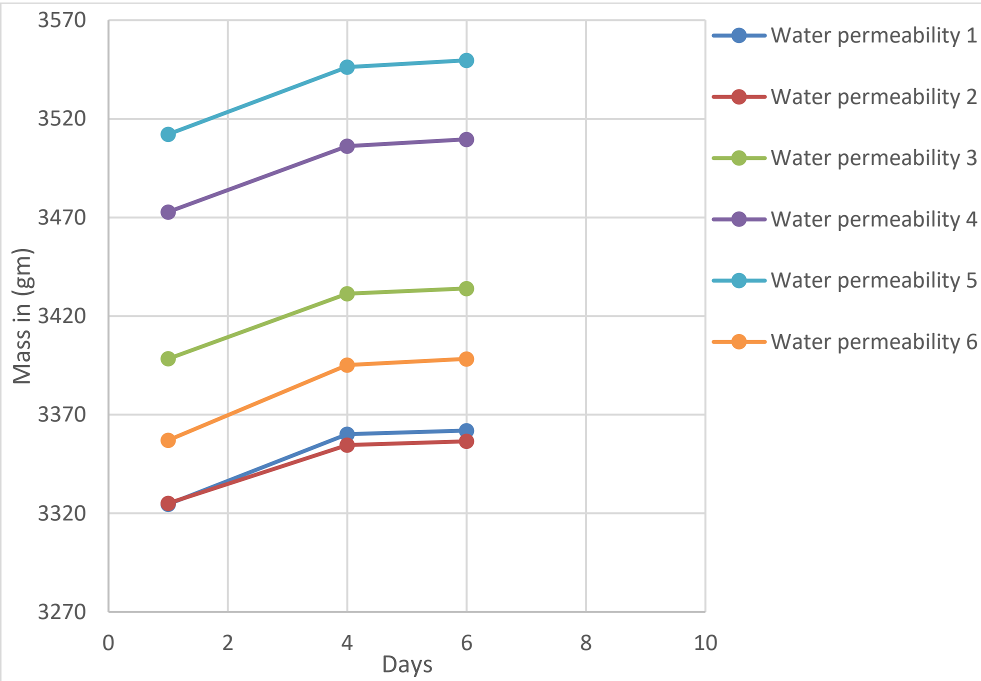
Table (3. 21): Freeze-thaw mass measurement



The water permeability through the pores and voids between cement particles and also between cement and aggregates particles in concrete specimens of size 150 x 150 x 70 mm was investigated, according to table (3.22).

The mass of specimen (w_n) in (gm)						
Days	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Specimen 4**	**Specimen 5**	**Specimen 6**
1st	3324.60	3325.07	3398.32	3472.77	3512.13	3357.03
4th	3360.03	3354.58	3431.30	3506.18	3546.20	3395.13
6th	3361.96	3356.50	3434	3509.6	3549.66	3398.31

Table (3. 22): Water permeability mass measurements



The results show almost a zero degradation in the concrete specimens, due to the replacement of 20% of stone sludge with cement. The mass loss due to the invoked damage in the concrete specimens was calculated by investigating the scaled material in table (3.23)

The scaled material (μ_s) in (gm)						
Cyclic attacks	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Specimen 4**	**Specimen 5**	**Specimen 6**
8	0.84	0.66	0.54	0.54	0.55	0.51

Table (3. 23): Scaled material

The dynamic modulus of elasticity (E_{Dyn}) is derived from the relative ultrasonic transit time (τ_n), using equation $\tau_n = \frac{tcs-tc}{tn-tc}$, where ($t_{cs}$) is transit time before the freeze and thaw cycles (capillary suction) and (t_n) is the total transit time after all cycles.

Consequently, micro-cracks start to evolve in the block, which lead to water penetration through the cracks to the pores. During the freezing process, the water in the pores freeze and cause expansion tension in the surrounding concrete. That decreases the strengths and evolves more cracks. It is worth considering the level of homogeneity and uniformity of the mixture when assessing the evolution of internal cracks.

As a conclusion, it was observed an enhancement in the freeze and thaw resistance with the increase of stone sludge powder in the concrete blocks. This is ascribed to the reduction in the water absorption, due to the fewer pores and voids. Thus, it is less affected with the cyclic freeze and thaw attacks.*

* *The freeze-thaw tests are scheduled to be continued until the 28th cycle of freeze thaw. These additional results will be added to the thesis as an appendix.*

3.9.2. Depth of penetration of water under pressure

The test aims to investigate the improvement in the liquid penetration of concrete blocks of size 150 x 150 x 150 mm, at a replacement rate of 20% of stone with cement at curing age of 28 days. The capillary pores in concrete has a deteriorating effect on it. Thus, the less capillary absorption it has, the less liquid penetration across the concrete, which has a hydraulic potential, affecting concrete negatively.

The ingredients of concrete mixture were added in accordance with the code (DIN EN 12390). The table (3.24) shows the ratios of the concrete mix.

During the mixing process the aggregates are added coarse first then finer respectively. The aggregates were mixed with doses of water and left to for a minute to saturate.

Consequently, the cement with 20% stone sludge replacement by weight were mixed for a couple of minutes with the last dose of water. It is worth mentioning that, during the mixing process the concrete mixture hardened, due to the increase in the water demand because of the stone sludge addition. Thus, an addition of a 27 gm superplasticizer in total, which were added in two doses during the mixing, to enhance the rheological behaviour of the cement paste. Consequently, the workability got positively affected. Moreover, the temperature of the concrete paste after the mix was recorded at 24.4 °C, whereas the room temperature was recorded at 22 °C.

Cement CEM I 42.5N	**Stone sludge 20 in (%)**	**Aggregates in (kg)**				**Water in (Litre)**	**Superplasticizer admixture in (gm)**
		0/2	2/4	4/8	8/16		
5.20	1.30	11.5	7.6	7.6	11.5	3.25	14 gm 13 gm
		38.2					

Table (3. 24): Ingredients ratios of the concrete mix

The concrete moulds were kept in the damp storage room, to keep the moisture content of specimens for 24 hours.

After de-moulded the concrete blocks one side is roughly brushed with a metal brush, kept in the water sink for the whole period.

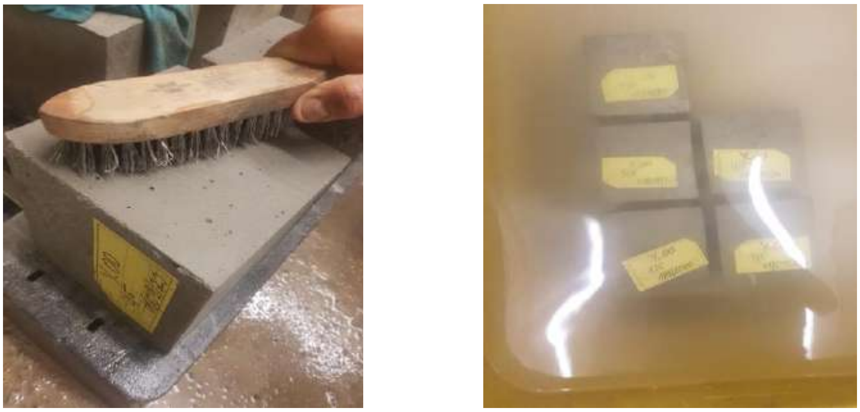


Figure (3. 21): Concrete blocks after de-moulding

The test started on the 42nd day of curing age. Whereas the concrete blocks were subjected to a water pressure of 5 bar, applied to the brushed surface of the specimens for a period of 72 hours. Afterwards, the specimens were crushed under pressure, to identify the water penetration, as in table (3.25).

Specimen	Y_00_01	Y_00_02	Y_00_03	Y_00_04	Y_00_05
Water penetration in (mm)	8	9	10	10	12

Table (3. 25): Water penetration measurements

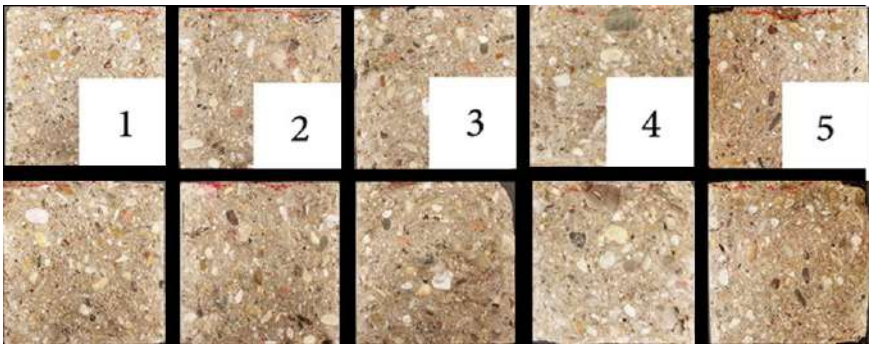


Figure (3. 22): Measuring water penetration

Figure (3. 23): Crushing specimens

As a conclusion, it was observed a decrease in the water absorption with the increase of stone sludge powder in the concrete block. This is ascribed to the high Blaine fineness, and the high filling ability of stone sludge particles.

3.10. Prospective tests

3.10.1. Morphology

Topographical image of specimen under an electron scanning microscope.

3.10.2. Thermo-gravimetric analysis

TGA (Thermo-gravimetric analysis) is a precisely precise quantitative measurement of the weight change of a solid concrete, due to dehydration, oxidation and decomposition, when it is heated at a constant rate of 30 °C to 900 °C at a constant rate of 10 °C/min.

3.10.3. Modulus of elasticity

3.10.4. Abrasion resistance test

(Los Angeles abrasion test on aggregate)

The improvement in the abrasive wear that occurs on the surface of concrete. The abrasion occurs due to the pores on the surface allowing the penetration of particles that leads to the wear of the surface of concrete.

3.10.5. Resistance to Carbonation, Chloride migration and Corrosion tests

The improvement in the resistance to Carbonation, Chloride migration and corrosion when manufacturing concrete using different water/cement ratios and substitution percentages of cement by stone sludge at percentages 10%, 20%,30% and 40%. The specimens are subjected to an accelerated carbonation process and exposure to different chloride levels, to characterize the corrosion level of each. Which causes deterioration processes to concrete due to carbonation or chloride induced de-passivation of steel bars. Resulting in the diffusion of gases, liquid or solid compounds in the pores of the concrete. (Physiochemical process).

3.10.6. Porosity test

The concrete is subjected to mercury (Hg) under external pressure.

The amount of mercury intrusion is measured by Porosimeter. Then, all the factors that are associated with porosity size, volume, distribution and density of pores are evaluated, according to the Washburn equation.

4. Conclusion and Discussion

The surge for finding reliable resources that capacitate us on the planet is inevitable. The high demand on building materials due to the high rate of construction increasing exponentially to cope with the increasing population.

Whilst, the discarded waste from all the industries that operate currently could be incorporated in many industries. The stone waste due to the extraction and processing causes the proliferation of the disposal sites, which is a contingent factor in the stone industry equation. Despite, the daunting task that awaits during the collection, sorting, separation, shipping and reprocessing, it is still a remarkable economic alternative and an environmental desperate call to sustain us in an infinite loop of generation.

Due to the overarching problem of environmental pollution, including air, water and soil pollution, which is adversely affecting the flora and fauna, the idea arises of the re-using and recycling of the by-product of the stone processing industry by incorporating it in the cement and concrete production. The high percentage of calcium content in the stone sludge waste makes it an easy and cheap material in the construction sector, which absorbs a high amount of material during the process. Building materials are highly consumed in various industries, like bricks, plastics, pottery, ceramics, paint, cement composites, desulphurization and infiltration processes, in addition to geo-polymer composite materials.

In this research, it has been demonstrated that the replacement of stone sludge powder is not to the detriment of concrete, in all aspects with regards to the chemical, sieve and laser analysis.

In the endeavour of validating and licensing the product in the construction sector, all the results obtained during the durability and quality tests of concrete satisfy with the European standards and norms, in order to ensure the safety and performance efficiency of usage in construction.

Meanwhile, Portland cement is partially replaced using an inert filler like stone sludge, it inevitably results in reduced the mechanical properties (strength). However, considering the modern tendencies in the cement industry of an ever-increasing cement strength, this (relatively low) reduction of strength due to stone sludge inclusion is not critical for the vast majority of conventional applications and even in high strength concrete. In many instances, a certain limitation of a higher concrete strength is even desired (for example, with respect to minimum reinforcement requirements or with respect to the maximum over strength relevant for seismic considerations). Since the cement industry tends to produce ever-finer cements with consequently ever-increasing strength, the addition of stone sludge can be used to fine-tune the strength requirement and avoid unnecessary over strength as well as to maintain the workability of concrete. Finally, this approach would also lead to a more economical concrete.

The present study demonstrated that the addition of stone sludge has no adverse effect on the durability of concrete. However, additional tests are required to fully verify these findings.

To conclude, fine stone sludge is a versatile filler with great potential in the new era of concrete technology, with engineers striving towards performance based design of concrete with respect to its properties in fresh and hardened state, as well as durability. On the other side, the use of stone sludge in concrete could lead to a significantly reduced environmental impact from the stone processing industry. Finally, the low cost of the stone sludge as waste material could substantially reduce the price of concrete.

5. Case study

A residential compound consisting of 13 blocks. Each building is five-storeys. Whereas, the floor has 4 apartments 80-metre square each. This project required a minimum of concrete strengths 25 MPa. Thus, the 40% replacement of stone sludge powder with cement lies in the range of the minimum requirement.

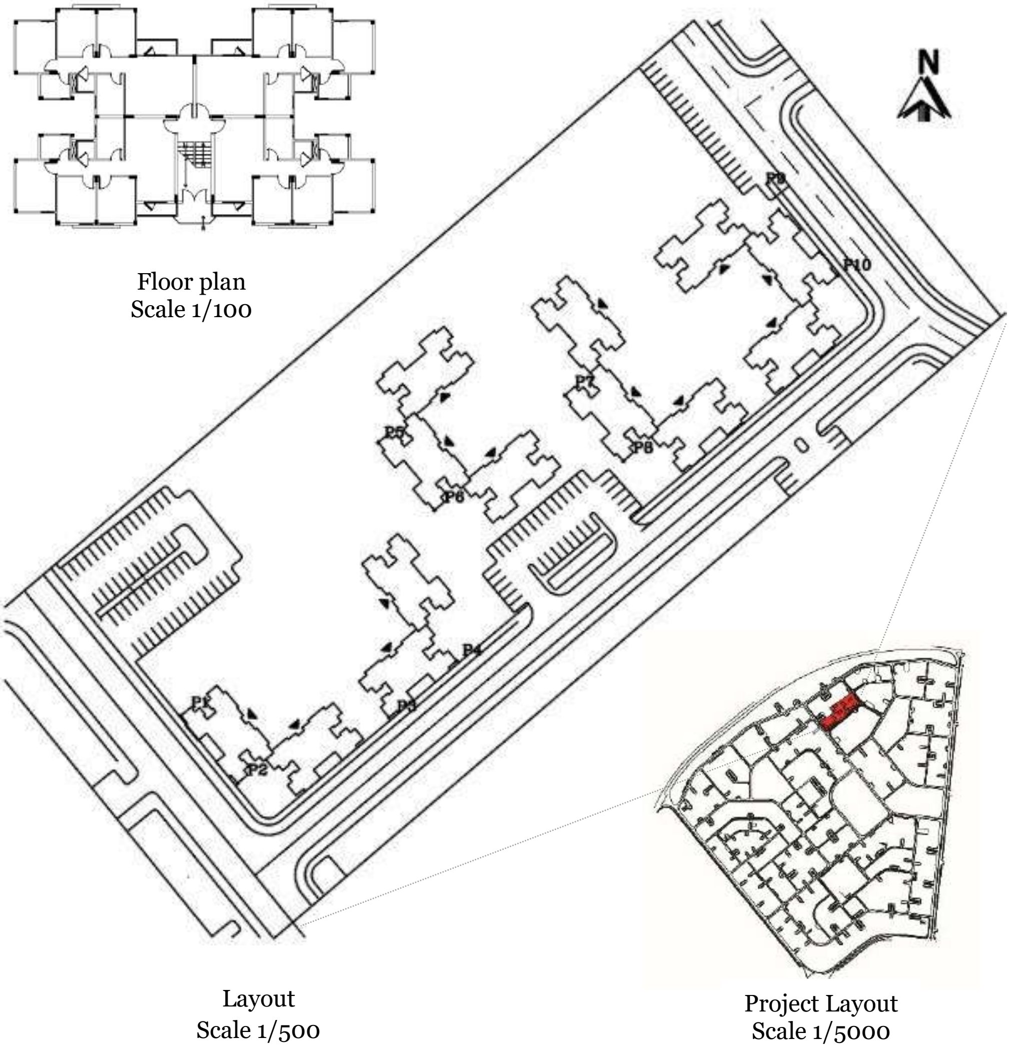


Figure (5. 1): Project design drawings

Comparative analysis for the whole project of 13 building blocks

<table>
<tr><th>P.C. foundation in m^3</th><th>R.C. foundation in m^3</th><th>R.C. columns in m^3</th><th>R.C. slabs in m^3</th><th>Bricks in m^3</th><th>Interlock in m^2</th></tr>
<tr><td rowspan="3">2600</td><td>2600</td><td>1430</td><td>5330</td><td rowspan="3">7000</td><td rowspan="3">5000</td></tr>
<tr><td colspan="3">Total R.C.</td></tr>
<tr><td colspan="3">9360</td></tr>
</table>

Table (5. 1): Bill Of Quantity (BOQ)

The table (5.1) shows the quantities of relevant building material used in the project. Meanwhile, the amount of concrete used could be estimated at twelve thousand metre cube 12000 m^3. By which, the replacement rates with stone sludge could be incorporated to reduce significant amounts of cement.
In case of replacing stone sludge with cement, at the replacement rates 10, 20, 30 and 40%, it can be estimated a reduced rates of cement at 385, 769, 1153 and 1537 tons respectively. According to the ratio (1:2:4) of sand, aggregate (gravel) and cement respectively, as in table (5.2).

Replacement rates of sludge in %	10	20	30	40
Reduction rates of cement in Tons	385	769	1153	1537

Table (5. 2): Reduction rates of cement

In addition to the significant amount of bricks and landscape interlock bricks, which would absorb a lot of stone sludge if replaced with cement.
The results show that the implementation of stone sludge powder in the concrete industry could be a cost-effective alternative in order to minimize the adverse impact on the environment from the disposal of the stone production industry waste.

It is of great importance to assess the return on investment (ROI). As indicated in the quantitative analysis, it can be concluded that the cost analysis of the cubic metre of concrete is affected inversely with the replacement rates of stone sludge in it.

Whereas, with 7% and 20% marble sludge powder replacement with cement, the cost reduces by 10 and 24% respectively. (76)
On the other hand, when studying the environmental effect of ordinary Portland cement (OPC). It is estimated that the cement industry is responsible for about 7% of all carbon dioxide (CO_2) emitted all over the world. (77)
While, in the brick industry, it is estimated that 0.41 kg of carbon dioxide (CO_2) is emitted per brick. (78)

It could be concluded that the incorporation of stone sludge powder in concrete industry would reduce the carbon footprint of concrete, in addition to reducing the pollution generated form the whole industry. Consequently, adding more value to the product and affecting the final cost of stone products. Thus, the by-product of stone processing plants could be commercialized and sold in the market.

The strengths of concrete reduction can be parametrized by incorporating high strength cement that requires more grinding which does not consume a significant amount of energy relatively. Moreover, the use of superplasticizer admixtures and manipulating the water to binder ratio could compensate the loss in the strengths.

Ultimately, it could be incorporated on a wide range of practice in residential buildings where high strength concrete is not so significant. The use of stone waste powder has a synergic effect positively on the environment, flora and fauna, in addition to reducing the carbon footprint of cement, as a result of less energy consumption.

6. Decision making (SWOT analysis)

The strengths of replacing stone sludge as a cement additive is reducing its carbon footprint, in addition to its cost reduction. Therefore, this could be a feasible solution for the by-product of the stone industry, in addition to affecting the end-product cost. Most importantly a non-detrimental addition in concrete, reducing the bad effects of disposing of the sludge waste. Besides, the cheap price of the stone sludge in comparison to the increasing price of cement due to the depletion of the resources and the alarming climatic changes.

On the contrary, the weaknesses could be summarized in the difficulties of collecting and shipping the sludge waste. Moreover, the drying and grinding processes are considered among the drawbacks, which need machinery on a bigger scale to satisfy the increasing demand. Apart from adding a higher carbon footprint factor to the equation of sustainability, there is a slight decrease in the concrete properties, however having a positive durability performance upon it.

Whereas, creating more opportunities in both cement and stone industries. It could act as an economical profit-incurring national project that could be an attractive investment for capitalists on a wide industrial scale. Whether by collecting and selling the un-treated stone sludge as a raw material, or by treating and selling as a cement additive, using the cement plants heat for drying the sludge and the grinders available to pulverize it.

Nonetheless, there are few threats in the way of achieving the prospective potential investment project. It is hard to invoke a new culture that has long been implemented. In addition, the acceptance and compliance from local residence could be an obstacle in the way of achieving the project. The localization and distance proximity of stone processing plants to the cement plants adds to the decision making process in order to weigh the risks and the benefits.

At the end, the user has the variety to choose between the several possibilities and compensate the best trade-off.

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Appendix (I) Y_00 analysis

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_00_Ref	0	1	Friday, May 22, 2020	16:45		28	Friday, June 19, 2020	594.50	40	40	2.69	
Y_00_Ref	0	2	Friday, May 22, 2020	16:45	220.0	28	Friday, June 19, 2020	598.70	40	40	2.67	2.68
Y_00_Ref	0	3	Friday, May 22, 2020	16:45		28	Friday, June 19, 2020	596.70	40	40	2.68	
Y_00	10	1	Friday, May 22, 2020	17:15		28	Friday, June 19, 2020	583.1	40	40	2.74	
Y_00	10	2	Friday, May 22, 2020	17:15	215.0	28	Friday, June 19, 2020	586.7	40	40	2.73	2.75
Y_00	10	3	Friday, May 22, 2020	17:15		28	Friday, June 19, 2020	578.5	40	40	2.77	
Y_00	20	1	Friday, May 22, 2020	17:45		28	Friday, June 19, 2020	581.9	40	40	2.75	
Y_00	20	2	Friday, May 22, 2020	17:45	220.0	28	Friday, June 19, 2020	583.4	40	40	2.74	2.75
Y_00	20	3	Friday, May 22, 2020	17:45		28	Friday, June 19, 2020	581.7	40	40	2.75	
Y_00 //	30	1	Thursday, July 9, 2020	15:45		28	Thursday, August 6, 2020	581.9	40	40	2.75	
Y_00 //	30	2	Thursday, July 9, 2020	15:45		28	Thursday, August 6, 2020	580	40	40	2.76	2.77
Y_00 //	30	3	Thursday, July 9, 2020	15:45		28	Thursday, August 6, 2020	572.2	40	40	2.80	
Y_00 //	40	1	Thursday, July 9, 2020	15:30		28	Thursday, August 6, 2020	570.5	40	40	2.80	
Y_00 //	40	2	Thursday, July 9, 2020	15:30		28	Thursday, August 6, 2020	567.7	40	40	2.82	2.83
Y_00 //	40	3	Thursday, July 9, 2020	15:30		28	Thursday, August 6, 2020	558	40	40	2.87	

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_00_Ref //	0	1	Tuesday, June 2, 2020	15:15		7	Tuesday, June 9, 2020	581.00	40	40	2.75	
Y_00_Ref //	0	2	Tuesday, June 2, 2020	15:15		7	Tuesday, June 9, 2020	584.10	40	40	2.74	2.74
Y_00_Ref //	0	3	Tuesday, June 2, 2020	15:15		7	Tuesday, June 9, 2020	585.80	40	40	2.73	
Y_00 //	10	1	Tuesday, May 26, 2020	15:20		7	Tuesday, June 2, 2020	583	40	40	2.74	
Y_00 //	10	2	Tuesday, May 26, 2020	15:20	205.0	7	Tuesday, June 2, 2020	587.4	40	40	2.72	2.74
Y_00 //	10	3	Tuesday, May 26, 2020	15:20		7	Tuesday, June 2, 2020	584.6	40	40	2.74	
Y_00 //	20	1	Tuesday, May 26, 2020	15:45		7	Tuesday, June 2, 2020	576.3	40	40	2.78	
Y_00 //	20	2	Tuesday, May 26, 2020	15:45	207.0	7	Tuesday, June 2, 2020	581.1	40	40	2.75	2.76
Y_00 //	20	3	Tuesday, May 26, 2020	15:45		7	Tuesday, June 2, 2020	579.5	40	40	2.76	
Y_00	30	1	Wednesday, May 27, 2020	15:30		7	Wednesday, June 3, 2020	563.7	40	40	2.84	
Y_00	30	2	Wednesday, May 27, 2020	15:30	217.5	7	Wednesday, June 3, 2020	565.9	40	40	2.83	2.83
Y_00	30	3	Wednesday, May 27, 2020	15:30		7	Wednesday, June 3, 2020	563.6	40	40	2.84	
Y_00	40	1	Wednesday, May 27, 2020	15:55		7	Wednesday, June 3, 2020	556.5	40	40	2.88	
Y_00	40	2	Wednesday, May 27, 2020	15:55	212.0	7	Wednesday, June 3, 2020	558.5	40	40	2.86	2.87
Y_00	40	3	Wednesday, May 27, 2020	15:55		7	Wednesday, June 3, 2020	558.1	40	40	2.87	

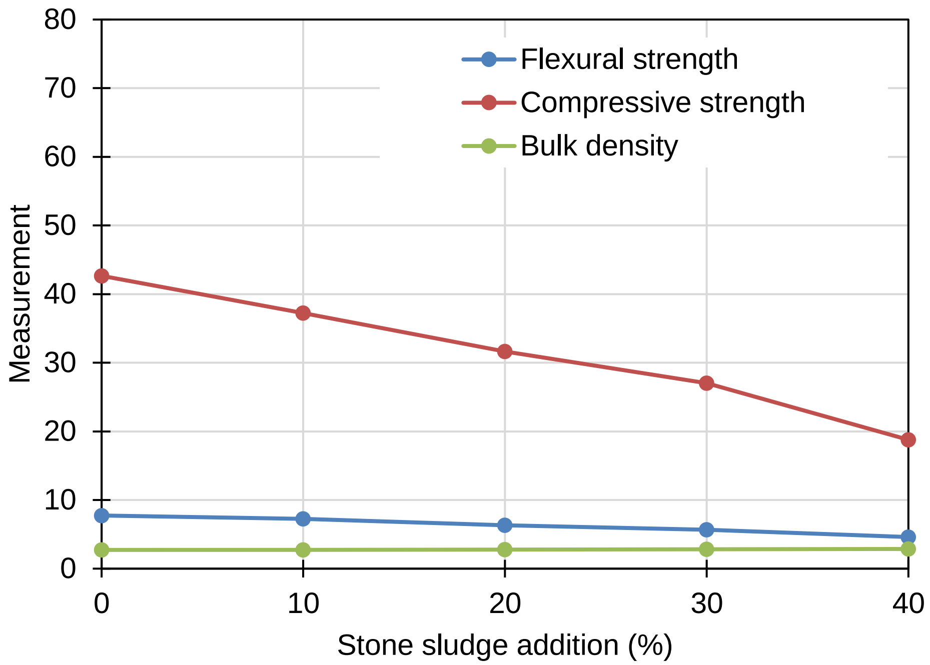
Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_00 // //	20	1	Thursday, July 9, 2020	16:15		56	Thursday, September 3, 2020	575.7	40	40	2.78	
Y_00 // //	20	2	Thursday, July 9, 2020	16:15	209.5	56	Thursday, September 3, 2020	576.3	40	40	2.78	2.78
Y_00 // //	20	3	Thursday, July 9, 2020	16:15		56	Thursday, September 3, 2020	575.2	40	40	2.78	
Y_00 // //	40	1	Thursday, July 9, 2020	16:30		56	Thursday, September 3, 2020	577.1	40	40	2.77	
Y_00 // //	40	2	Thursday, July 9, 2020	16:30	213.5	56	Thursday, September 3, 2020	576.6	40	40	2.77	2.79
Y_00 // //	40	3	Thursday, July 9, 2020	16:30		56	Thursday, September 3, 2020	567.5	40	40	2.82	

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.911	3.80	9.166	8.905	96.10	98.69	1.90%	60.06	61.68	1.90%
				100.30			62.69		
3.638		8.527		97.97			61.23		
				99.23			62.02		
3.849		9.021		101.11			63.19		
				97.41			60.88		
3.376	3.30	7.913	7.740	75.72	76.91	1.43%	47.33	48.07	1.43%
				77.00			48.13		
3.127		7.329		77.30			48.31		
				75.57			47.23		
3.404		7.978		78.47			49.04		
				77.40			48.38		
3.248	3.05	7.613	7.155	63.55	63.14	1.58%	39.72	39.46	1.58%
				62.84			39.28		
2.949		6.912		63.26			39.54		
				63.00			39.38		
2.962		6.942		64.63			40.39		
				61.58			38.49		
3.052	2.92	7.153	6.839	61.12	58.23	3.74%	38.20	36.39	3.74%
				56.65			35.41		
2.879		6.748		60.31			37.69		
				56.37			35.23		
2.823		6.616		58.85			36.78		
				56.06			35.04		
2.898	2.66	6.792	6.224	47.52	45.34	2.78%	29.70	28.34	2.78%
				45.64			28.53		
2.55		5.977		44.14			27.59		
				44.82			28.01		
2.519		5.904		45.69			28.56		
				44.22			27.64		

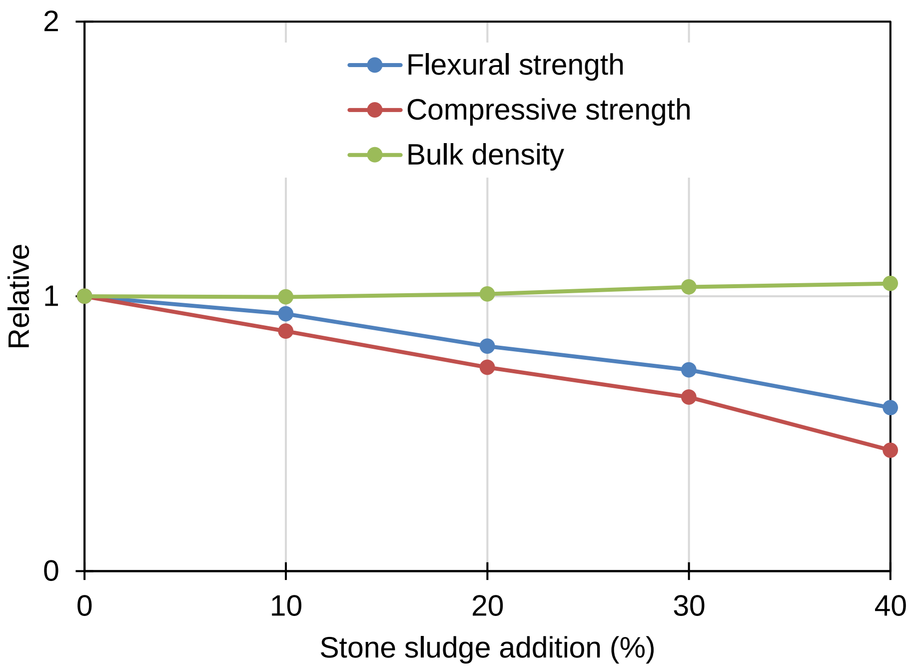
Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.389	3.30	7.943	7.739	67.42	68.26	2.30%	42.14	42.66	2.30%
				65.73			41.08		
3.343		7.835		68.09			42.56		
				70.14			43.84		
3.174		7.439		69.42			43.39		
				68.77			42.98		
2.996	3.09	7.022	7.246	59.77	59.61	2.77%	37.36	37.25	2.77%
				59.27			37.04		
3.184		7.463		62.12			38.83		
				60.16			37.60		
3.095		7.254		57.01			35.63		
				59.31			37.07		
2.698	2.70	6.323	6.338	51.27	50.64	1.64%	32.04	31.65	1.64%
				49.32			30.83		
2.71		6.352		50.17			31.36		
				51.60			32.25		
2.705		6.340		51.01			31.88		
				50.48			31.55		
2.531	2.42	5.932	5.671	43.72	43.23	1.55%	27.33	27.02	1.55%
				44.03			27.52		
2.326		5.452		43.63			27.27		
				43.07			26.92		
2.402		5.630		42.50			26.56		
				42.43			26.52		
1.958	1.96	4.589	4.605	29.11	30.05	2.55%	18.19	18.78	2.55%
				30.28			18.93		
2.048		4.800		30.67			19.17		
				29.24			18.28		
1.888		4.425		29.95			18.72		
				31.02			19.39		

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.373	3.31	7.905	7.764	73.27	73.15	1.68%	45.79	45.72	1.68%
				73.56			45.98		
3.296		7.725		72.16			45.10		
				74.24			46.40		
3.269		7.662		71.26			44.54		
				74.43			46.52		
2.74	2.71	6.422	6.360	48.00	48.03	4.11%	30.00	30.02	4.11%
				50.48			31.55		
2.96		6.938		47.55			29.72		
				48.50			30.31		
2.441		5.721		44.58			27.86		
				49.07			30.67		

At 7 days

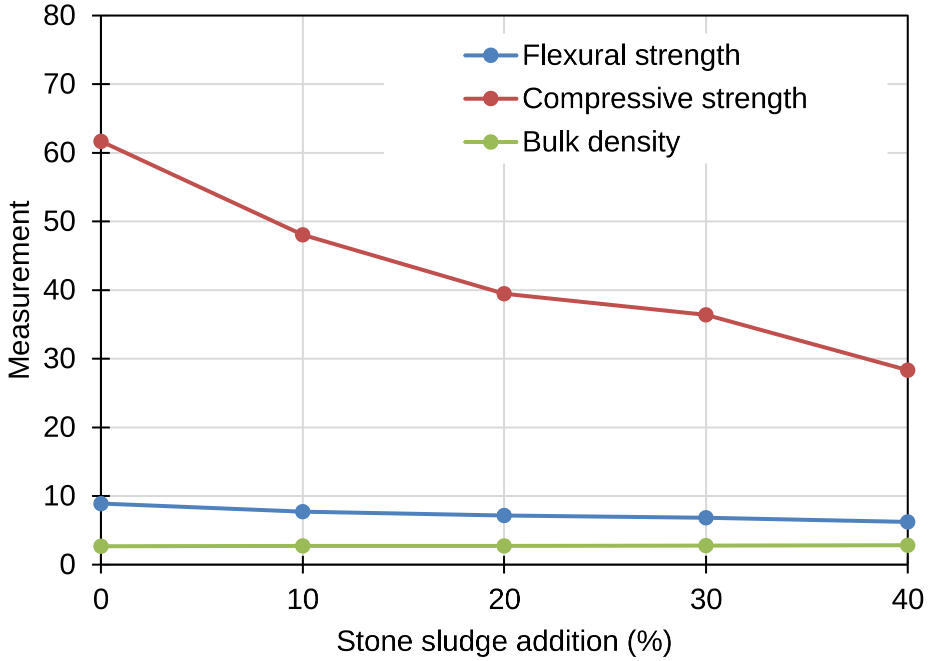


80
70
60
50
40
30
20
10
0
Measurement
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)



2
1
0
Relative
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)

At 28 days



80
70
60
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40
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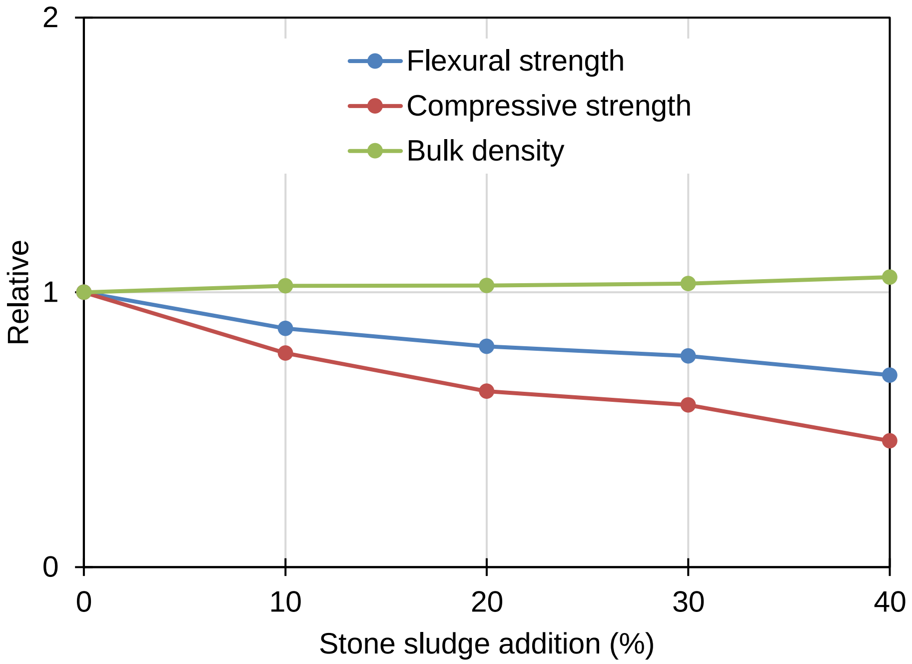
20
10
0
Measurement
0
10
20
30
40
Stone sludge addition (%)
Flexural strength
Compressive strength
Bulk density



2
1
0
Relative
0
10
20
30
40
Stone sludge addition (%)
Flexural strength
Compressive strength
Bulk density

Appendix (II) Y_01 analysis

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_01	10	1	Wednesday, June 24, 2020	16:45		28	Wednesday, July 22, 2020	586.6	40	40	2.73	
Y_01	10	2	Wednesday, June 24, 2020	16:45	220.0	28	Wednesday, July 22, 2020	587.7	40	40	2.72	2.74
Y_01	10	3	Wednesday, June 24, 2020	16:45		28	Wednesday, July 22, 2020	577.9	40	40	2.77	
Y_01	20	1	Tuesday, June 16, 2020	15:00		29	Wednesday, July 15, 2020	569.7	40	40	2.81	
Y_01	20	2	Tuesday, June 16, 2020	15:00	216.5	29	Wednesday, July 15, 2020	571.3	40	40	2.80	2.81
Y_01	20	3	Tuesday, June 16, 2020	15:00		29	Wednesday, July 15, 2020	567.9	40	40	2.82	
Y_01	30	1	Wednesday, June 24, 2020	17:15		28	Wednesday, July 22, 2020	574	40	40	2.79	
Y_01	30	2	Wednesday, June 24, 2020	17:15	216.5	28	Wednesday, July 22, 2020	577.1	40	40	2.77	2.78
Y_01	30	3	Wednesday, June 24, 2020	17:15		28	Wednesday, July 22, 2020	575.5	40	40	2.78	
Y_01	40	1	Wednesday, June 24, 2020	17:45		28	Wednesday, July 22, 2020	570.1	40	40	2.81	
Y_01	40	2	Wednesday, June 24, 2020	17:45	217.5	28	Wednesday, July 22, 2020	572.8	40	40	2.79	2.81
Y_01	40	3	Wednesday, June 24, 2020	17:45		28	Wednesday, July 22, 2020	565.8	40	40	2.83	

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_01 //	10	1	Wednesday, July 15, 2020	16:15		7	Wednesday, July 22, 2020	587.2	40	40	2.72	
Y_01 //	10	2	Wednesday, July 15, 2020	16:15	223.0	7	Wednesday, July 22, 2020	584.2	40	40	2.74	2.74
Y_01 //	10	3	Wednesday, July 15, 2020	16:15		7	Wednesday, July 22, 2020	579.3	40	40	2.76	
Y_01 //	20	1	Wednesday, July 15, 2020	16:30		7	Wednesday, July 22, 2020	579	40	40	2.76	
Y_01 //	20	2	Wednesday, July 15, 2020	16:30	210.0	7	Wednesday, July 22, 2020	583.3	40	40	2.74	2.75
Y_01 //	20	3	Wednesday, July 15, 2020	16:30		7	Wednesday, July 22, 2020	581.8	40	40	2.75	
Y_01 //	30	1	Wednesday, July 15, 2020	16:45		7	Wednesday, July 22, 2020	572.4	40	40	2.80	
Y_01 //	30	2	Wednesday, July 15, 2020	16:45	211.8	7	Wednesday, July 22, 2020	576.5	40	40	2.78	2.80
Y_01 //	30	3	Wednesday, July 15, 2020	16:45		7	Wednesday, July 22, 2020	568.2	40	40	2.82	
Y_01 //	40	1	Wednesday, July 15, 2020	17:00		7	Wednesday, July 22, 2020	566.3	40	40	2.83	
Y_01 //	40	2	Wednesday, July 15, 2020	17:00	207.0	7	Wednesday, July 22, 2020	574.8	40	40	2.78	2.80
Y_01 //	40	3	Wednesday, July 15, 2020	17:00		7	Wednesday, July 22, 2020	574	40	40	2.79	

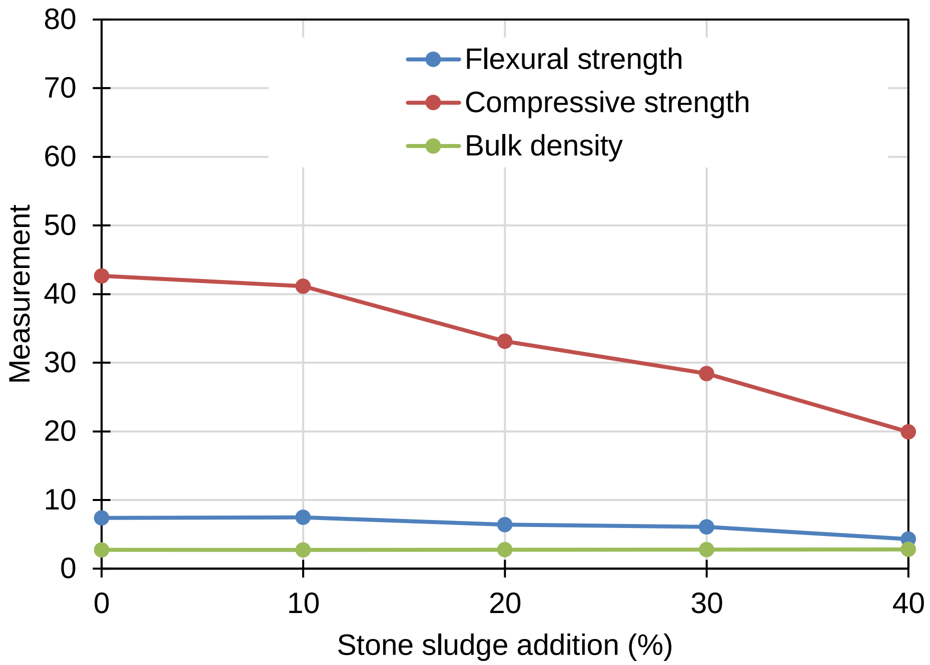
Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_01 // //	20	1	Tuesday, June 16, 2020	15:30		56	Tuesday, August 11, 2020	596	40	40	2.68	
Y_01 // //	20	2	Tuesday, June 16, 2020	15:30	218.0	56	Tuesday, August 11, 2020	595.2	40	40	2.69	2.69
Y_01 // //	20	3	Tuesday, June 16, 2020	15:30		56	Tuesday, August 11, 2020	594.5	40	40	2.69	
Y_01 // //	40	1	Tuesday, June 30, 2020	17:30		56	Tuesday, August 25, 2020	563.1	40	40	2.84	
Y_01 // //	40	2	Tuesday, June 30, 2020	17:30	207.0	56	Tuesday, August 25, 2020	560.7	40	40	2.85	2.85
Y_01 // //	40	3	Tuesday, June 30, 2020	17:30		56	Tuesday, August 25, 2020	560.7	40	40	2.85	

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.177	3.26	7.446	7.648	79.80	80.11	1.61%	49.88	50.07	1.61%
				78.24			48.90		
3.145		7.371		80.23			50.14		
				81.36			50.85		
3.468		8.128		81.71			51.07		
				79.33			49.58		
2.85	3.05	6.680	7.153	62.21	63.32	2.56%	38.88	39.58	2.56%
				63.27			39.54		
3.098		7.261		65.12			40.70		
				61.48			38.43		
3.208		7.519		65.43			40.89		
				62.42			39.01		
2.907	2.87	6.813	6.731	55.77	57.76	1.97%	34.86	36.10	1.97%
				57.38			35.86		
2.925		6.855		58.16			36.35		
				57.75			36.09		
2.784		6.525		59.09			36.93		
				58.42			36.51		
2.283	2.42	5.351	5.664	41.04	41.30	4.59%	25.65	25.81	4.59%
				42.37			26.48		
2.339		5.482		41.99			26.24		
				37.64			23.53		
2.628		6.159		41.90			26.19		
				42.88			26.80		

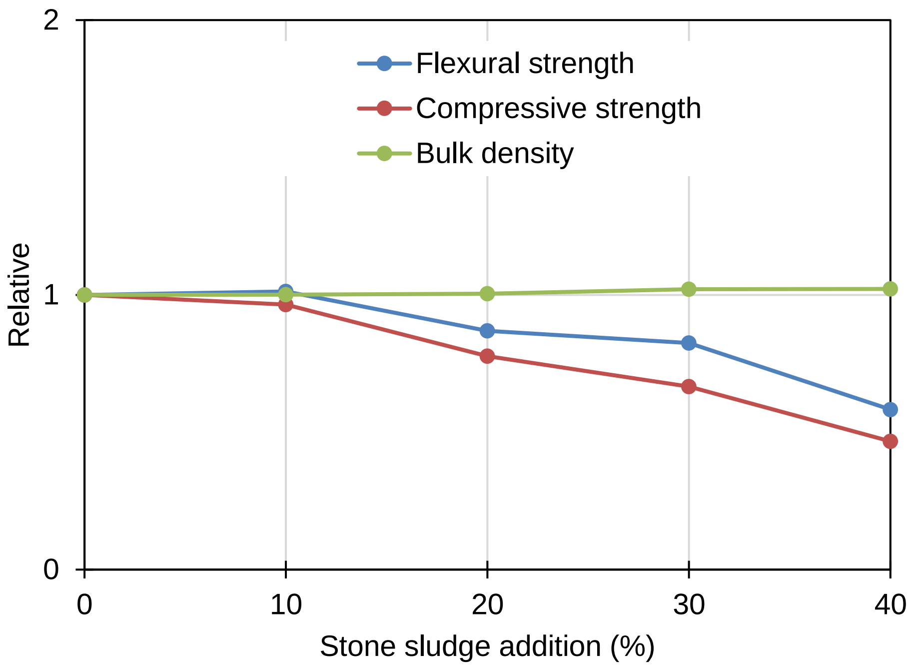
Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.333	3.19	7.812	7.470	69.26	65.82	6.41%	43.29	41.13	6.41%
				58.57			36.61		
3.112		7.294		67.44			42.15		
				69.83			43.64		
3.116		7.303		63.47			39.67		
				66.32			41.45		
2.638	2.74	6.183	6.410	58.49	53.01	23.20%	36.56	33.13	23.20%
				38.85			24.28		
2.783		6.523		61.87			38.67		
				60.17			37.61		
2.784		6.525		62.92			39.33		
				35.75			22.34		
2.763	2.60	6.476	6.083	47.51	45.48	6.71%	29.69	28.42	6.71%
				47.86			29.91		
2.63		6.164		44.25			27.66		
				39.90			24.94		
2.393		5.609		47.48			29.68		
				45.86			28.66		
1.853	1.83	4.343	4.300	32.10	31.87	3.84%	20.06	19.92	3.84%
				32.42			20.26		
2.001		4.690		29.46			18.41		
				32.07			20.04		
1.65		3.867		32.21			20.13		
				32.96			20.60		

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.82	3.79	8.953	8.893	73.27	73.15	1.68%	85.99	84.70	1.16%
				73.56			84.55		
3.793		8.890		72.16			83.71		
				74.24			84.26		
3.77		8.836		71.26			85.83		
				74.43			83.88		
2.68	2.68	6.281	6.284	48.00	48.03	4.11%	49.03	48.65	2.01%
				50.48			49.05		
2.83		6.633		47.55			47.53		
				48.50			47.69		
2.534		5.939		44.58			48.45		
				49.07			50.15		

At 7 days

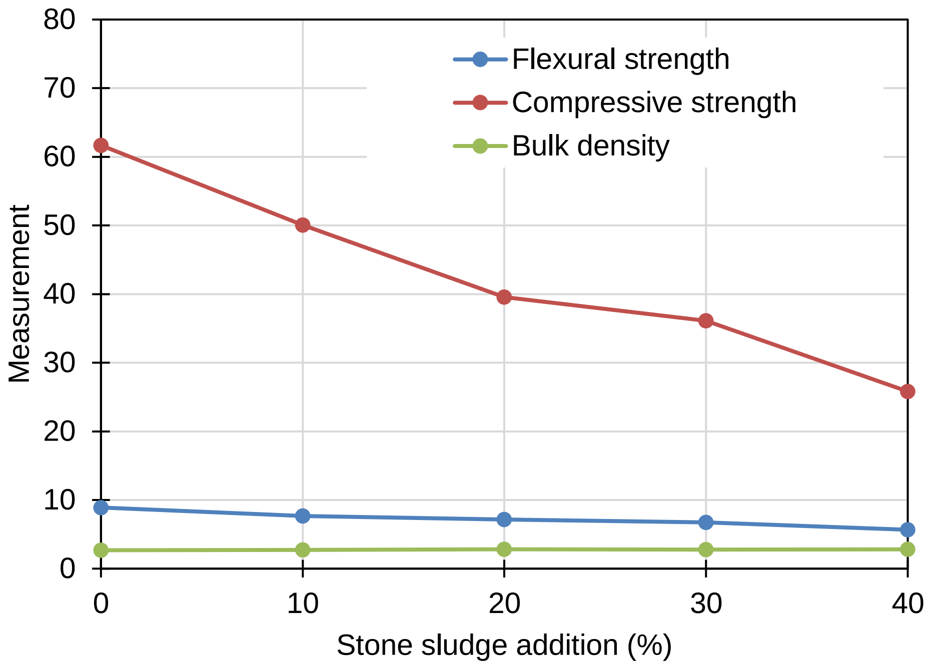


Flexural strength
Compressive strength
Bulk density
Measurement
80
70
60
50
40
30
20
10
0
0
10
20
30
40
Stone sludge addition (%)

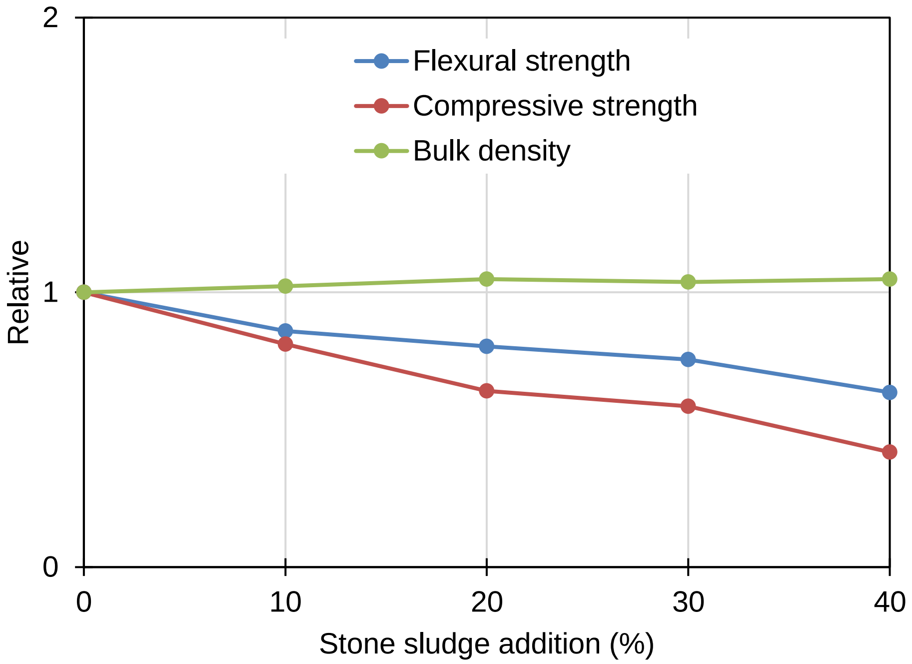


Flexural strength
Compressive strength
Bulk density
Relative
2
1
0
0
10
20
30
40
Stone sludge addition (%)

At 28 days



80
70
60
50
40
30
20
10
0
Measurement
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)



2
1
0
Relative
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)

Appendix (III) Y_02 analysis

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_02	10	1	Tuesday, June 30, 2020	16:15		28	Tuesday, July 28, 2020	583.3	40	40	2.74	
Y_02	10	2	Tuesday, June 30, 2020	16:15	211.0	28	Tuesday, July 28, 2020	590.3	40	40	2.71	2.74
Y_02	10	3	Tuesday, June 30, 2020	16:15		28	Tuesday, July 28, 2020	579.7	40	40	2.76	
Y_02	20	1	Tuesday, June 30, 2020	16:30		28	Tuesday, July 28, 2020	577.1	40	40	2.77	
Y_02	20	2	Tuesday, June 30, 2020	16:30	211.0	28	Tuesday, July 28, 2020	580	40	40	2.76	2.76
Y_02	20	3	Tuesday, June 30, 2020	16:30		28	Tuesday, July 28, 2020	578.9	40	40	2.76	
Y_02	30	1	Tuesday, June 30, 2020	16:45		28	Tuesday, July 28, 2020	568.2	40	40	2.82	
Y_02	30	2	Tuesday, June 30, 2020	16:45	210.0	28	Tuesday, July 28, 2020	573.2	40	40	2.79	2.80
Y_02	30	3	Tuesday, June 30, 2020	16:45		28	Tuesday, July 28, 2020	573.9	40	40	2.79	
Y_02	40	1	Tuesday, June 30, 2020	17:00		28	Tuesday, July 28, 2020	571.9	40	40	2.80	
Y_02	40	2	Tuesday, June 30, 2020	17:00	198.3	28	Tuesday, July 28, 2020	566.2	40	40	2.83	2.80
Y_02	40	3	Tuesday, June 30, 2020	17:00		28	Tuesday, July 28, 2020	574.2	40	40	2.79	

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_02 //	10	1	Tuesday, July 21, 2020	15:30		7	Tuesday, July 28, 2020	595.6	40	40	2.69	
Y_02 //	10	2	Tuesday, July 21, 2020	15:30	210.0	7	Tuesday, July 28, 2020	593.6	40	40	2.70	2.69
Y_02 //	10	3	Tuesday, July 21, 2020	15:30		7	Tuesday, July 28, 2020	592.3	40	40	2.70	
Y_02 //	20	1	Tuesday, July 21, 2020	16:00		7	Tuesday, July 28, 2020	586.8	40	40	2.73	
Y_02 //	20	2	Tuesday, July 21, 2020	16:00	200.0	7	Tuesday, July 28, 2020	586.9	40	40	2.73	2.73
Y_02 //	20	3	Tuesday, July 21, 2020	16:00		7	Tuesday, July 28, 2020	584.4	40	40	2.74	
Y_02 //	30	1	Tuesday, July 21, 2020	16:15		7	Tuesday, July 28, 2020	579.5	40	40	2.76	
Y_02 //	30	2	Tuesday, July 21, 2020	16:15		7	Tuesday, July 28, 2020	582.7	40	40	2.75	2.76
Y_02 //	30	3	Tuesday, July 21, 2020	16:15		7	Tuesday, July 28, 2020	577.9	40	40	2.77	
Y_02 //	40	1	Tuesday, July 21, 2020	16:30		7	Tuesday, July 28, 2020	573.5	40	40	2.79	
Y_02 //	40	2	Tuesday, July 21, 2020	16:30		7	Tuesday, July 28, 2020	573.4	40	40	2.79	2.79
Y_02 //	40	3	Tuesday, July 21, 2020	16:30		7	Tuesday, July 28, 2020	573.2	40	40	2.79	

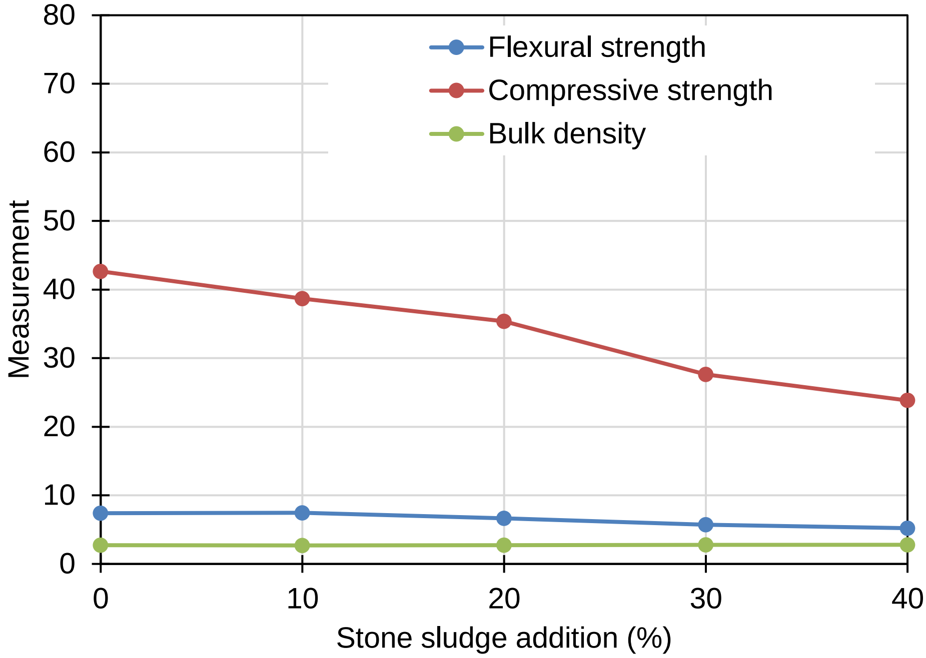
Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_02 ///	20	1	Tuesday, July 21, 2020	17:00		57	Wednesday, September 16, 2020	579.8	40	40	2.76	
Y_02 ///	20	2	Tuesday, July 21, 2020	17:00	207.5	57	Wednesday, September 16, 2020	581.3	40	40	2.75	2.76
Y_02 ///	20	3	Tuesday, July 21, 2020	17:00		57	Wednesday, September 16, 2020	580.7	40	40	2.76	
Y_02 ///	40	1	Tuesday, July 21, 2020	17:15		57	Wednesday, September 16, 2020	567.7	40	40	2.82	
Y_02 ///	40	2	Tuesday, July 21, 2020	17:15		57	Wednesday, September 16, 2020	572.7	40	40	2.79	2.82
Y_02 ///	40	3	Tuesday, July 21, 2020	17:15		57	Wednesday, September 16, 2020	564.1	40	40	2.84	

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.402	3.44	7.973	8.062	78.47	79.76	1.04%	49.04	49.85	1.04%
				80.10			50.06		
3.487		8.173		80.70			50.44		
				80.42			50.26		
3.43		8.039		79.21			49.51		
				79.63			49.77		
2.931	3.00	6.870	7.038	66.42	66.18	4.10%	41.51	41.36	4.10%
				67.26			42.04		
3.111		7.291		60.83			38.02		
				67.87			42.42		
2.966		6.952		66.53			41.58		
				68.16			42.60		
2.687	2.74	6.298	6.427	61.03	59.52	1.41%	38.14	37.20	1.41%
				59.62			37.26		
2.772		6.497		59.31			37.07		
				59.31			37.07		
2.767		6.485		58.47			36.54		
				59.39			37.12		
2.417	2.53	5.665	5.934	44.79	46.03	1.65%	27.99	28.77	1.65%
				46.60			29.13		
2.424		5.681		46.90			29.31		
				46.37			28.98		
2.755		6.457		45.72			28.58		
				45.80			28.63		

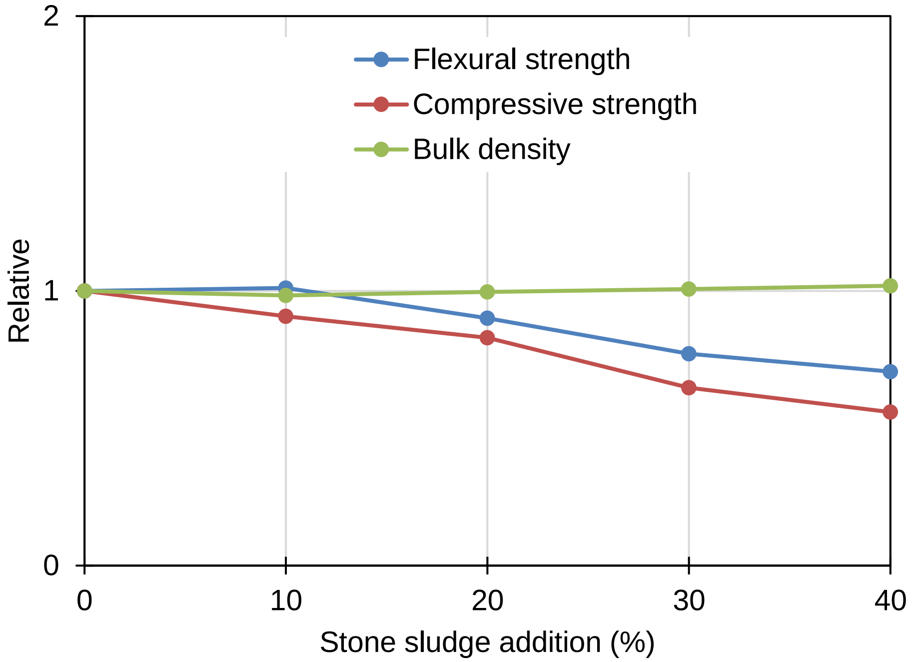
Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.24	3.18	7.594	7.456	64.44	61.92	5.94%	40.28	38.70	5.94%
				61.26			38.29		
3.06		7.172		56.74			35.46		
				64.02			40.01		
3.244		7.603		66.33			41.46		
				58.73			36.71		
2.729	2.83	6.396	6.641	54.68	56.61	2.32%	34.18	35.38	2.32%
				55.68			34.80		
2.845		6.668		57.27			35.79		
				56.99			35.62		
2.927		6.860		58.46			36.54		
				56.56			35.35		
2.471	2.43	5.791	5.693	44.59	44.21	4.78%	27.87	27.63	4.78%
				43.38			27.11		
2.272		5.325		42.85			26.78		
				41.55			25.97		
2.544		5.963		47.59			29.74		
				45.28			28.30		
2.269	2.22	5.318	5.211	38.11	38.13	2.63%	23.82	23.83	2.63%
				38.21			23.88		
2.199		5.154		38.81			24.26		
				39.59			24.74		
2.202		5.161		37.12			23.20		
				36.94			23.09		

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.215	3.28	7.535	7.698	74.80	74.63	1.24%	46.75	46.64	1.24%
				74.55			46.59		
3.133		7.343		74.21			46.38		
				73.69			46.06		
3.506		8.215		74.16			46.35		
				76.36			47.73		
2.611	2.57	6.120	6.028	44.87	44.81	4.11%	28.04	28.01	4.11%
				44.85			28.03		
2.574		6.033		46.27			28.92		
				47.32			29.58		
2.531		5.932		42.43			26.52		
				43.13			26.96		

At 7 days

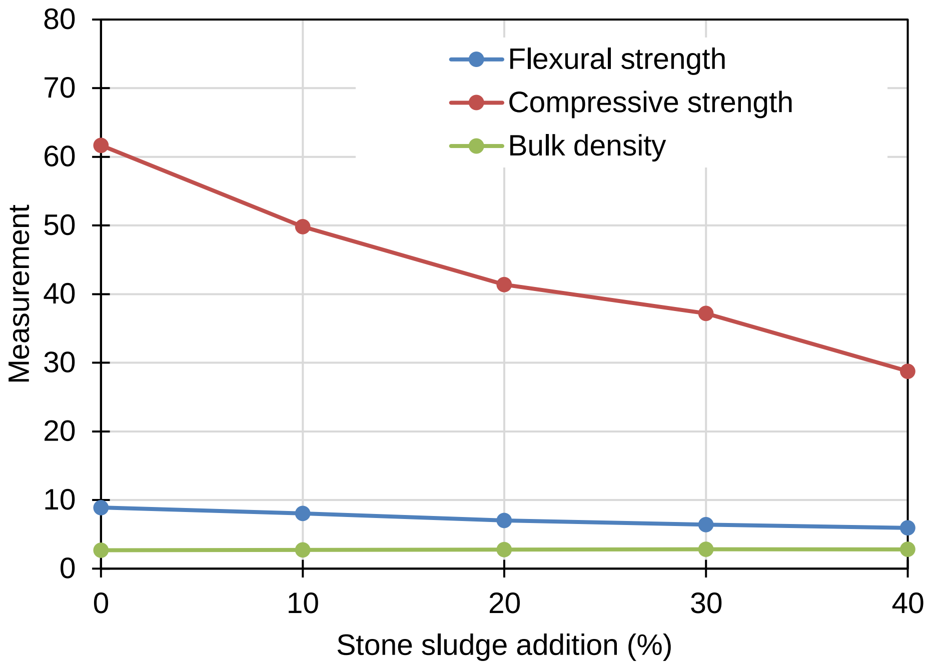


80
70
60
50
40
30
20
10
0
Measurement
0
10
20
30
40
Stone sludge addition (%)
Flexural strength
Compressive strength
Bulk density

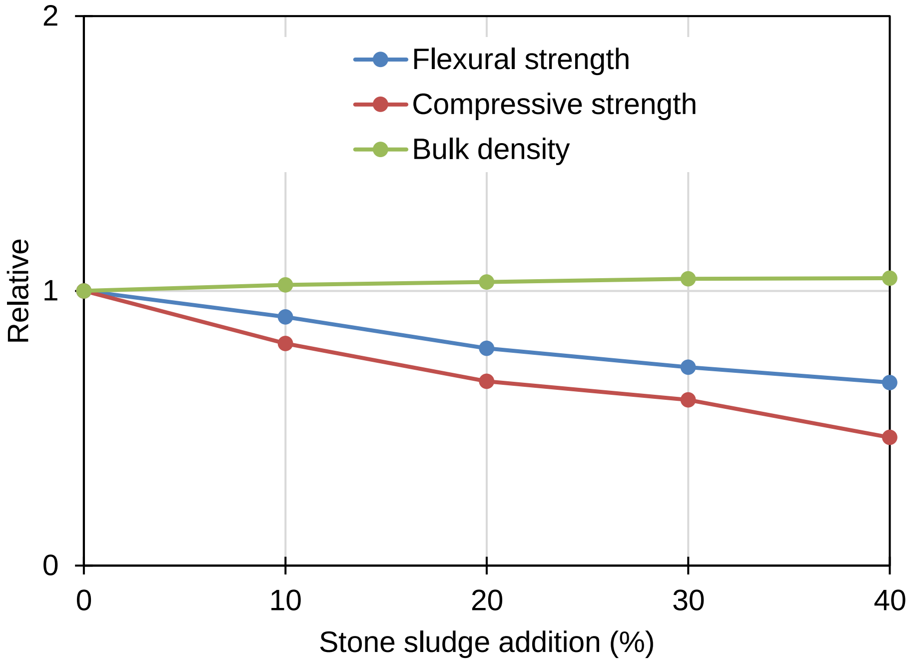


2
1
0
Relative
0
10
20
30
40
Stone sludge addition (%)
Flexural strength
Compressive strength
Bulk density

At 28 days



80
70
60
50
40
30
20
10
0
Measurement
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)



2
1
0
Relative
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)

Appendix (VI) Y_03 analysis

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_03	10	1	Thursday, July 2, 2020	16:15		28	Thursday, July 30, 2020	581.9	40	40	2.75	
Y_03	10	2	Thursday, July 2, 2020	16:15	212.5	28	Thursday, July 30, 2020	585.5	40	40	2.73	2.74
Y_03	10	3	Thursday, July 2, 2020	16:15		28	Thursday, July 30, 2020	582.5	40	40	2.75	
Y_03	20	1	Thursday, July 2, 2020	16:30		28	Thursday, July 30, 2020	578.5	40	40	2.77	
Y_03	20	2	Thursday, July 2, 2020	16:30	218.5	28	Thursday, July 30, 2020	578.5	40	40	2.77	2.76
Y_03	20	3	Thursday, July 2, 2020	16:30		28	Thursday, July 30, 2020	580.2	40	40	2.76	
Y_03	30	1	Thursday, July 2, 2020	16:45		28	Thursday, July 30, 2020	574	40	40	2.79	
Y_03	30	2	Thursday, July 2, 2020	16:45	202.0	28	Thursday, July 30, 2020	579.4	40	40	2.76	2.78
Y_03	30	3	Thursday, July 2, 2020	16:45		28	Thursday, July 30, 2020	571.9	40	40	2.80	
Y_03	40	1	Thursday, July 2, 2020	17:00		28	Thursday, July 30, 2020	568.9	40	40	2.81	
Y_03	40	2	Thursday, July 2, 2020	17:00	204.3	28	Thursday, July 30, 2020	573.4	40	40	2.79	2.80
Y_03	40	3	Thursday, July 2, 2020	17:00		28	Thursday, July 30, 2020	572.5	40	40	2.79	

Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_03 //	10	1	Thursday, July 23, 2020	15:30		7	Thursday, July 30, 2020	589.4	40	40	2.71	
Y_03 //	10	2	Thursday, July 23, 2020	15:30	217.5	7	Thursday, July 30, 2020	584.7	40	40	2.74	2.73
Y_03 //	10	3	Thursday, July 23, 2020	15:30		7	Thursday, July 30, 2020	581.7	40	40	2.75	
Y_03 //	20	1	Thursday, July 23, 2020	15:45		7	Thursday, July 30, 2020	583.7	40	40	2.74	
Y_03 //	20	2	Thursday, July 23, 2020	15:45	210.0	7	Thursday, July 30, 2020	583.4	40	40	2.74	2.75
Y_03 //	20	3	Thursday, July 23, 2020	15:45		7	Thursday, July 30, 2020	581.1	40	40	2.75	
Y_03 //	30	1	Thursday, July 23, 2020	16:00		7	Thursday, July 30, 2020	572.3	40	40	2.80	
Y_03 //	30	2	Thursday, July 23, 2020	16:00	207.0	7	Thursday, July 30, 2020	576.5	40	40	2.78	2.79
Y_03 //	30	3	Thursday, July 23, 2020	16:00		7	Thursday, July 30, 2020	573.4	40	40	2.79	
Y_03 //	40	1	Thursday, July 23, 2020	16:15		7	Thursday, July 30, 2020	568.8	40	40	2.81	
Y_03 //	40	2	Thursday, July 23, 2020	16:15	210.0	7	Thursday, July 30, 2020	567	40	40	2.82	2.81
Y_03 //	40	3	Thursday, July 23, 2020	16:15		7	Thursday, July 30, 2020	570	40	40	2.81	

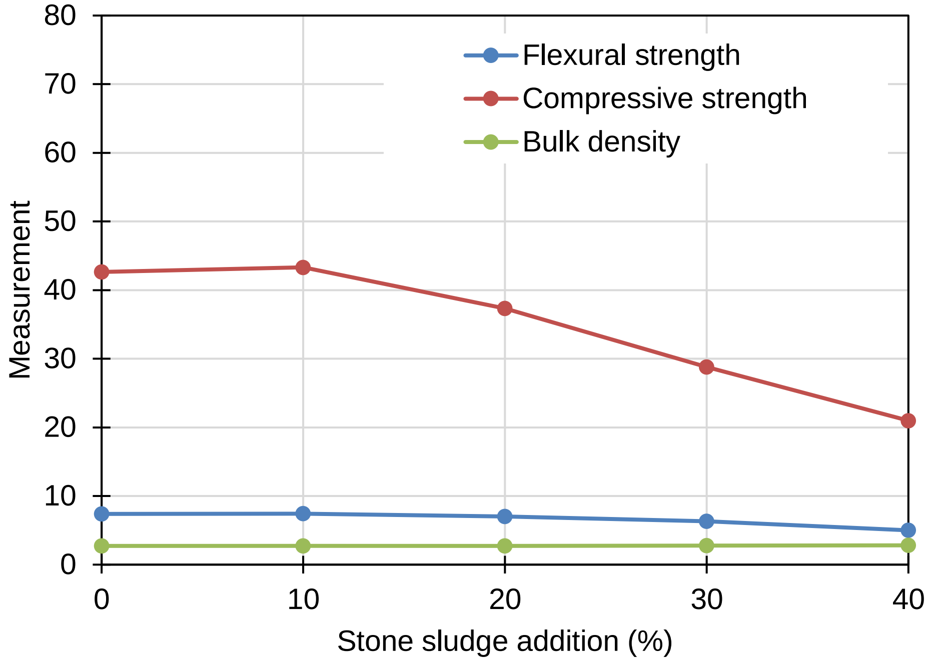
Specimen	Addition in %	Number	Casting-Date	Casting-time	Workability in mm	Test-age	Test-Date	Mass in g	Side a in mm	Side b in mm	Bulk density in kg/dm3	Average bulk density in kg/dm3
Y_03 // //	20	1	Thursday, July 2, 2020	17:30		56	Thursday, August 27, 2020	586.5	40	40	2.73	
Y_03 // //	20	2	Thursday, July 2, 2020	17:30	208.0	56	Thursday, August 27, 2020	579.4	40	40	2.76	2.74
Y_03 // //	20	3	Thursday, July 2, 2020	17:30		56	Thursday, August 27, 2020	585.1	40	40	2.73	
Y_03 // //	40	1	Thursday, July 9, 2020	16:45		56	Thursday, September 3, 2020	572.5	40	40	2.79	
Y_03 // //	40	2	Thursday, July 9, 2020	16:45	211.5	56	Thursday, September 3, 2020	573.1	40	40	2.79	2.79
Y_03 // //	40	3	Thursday, July 9, 2020	16:45		56	Thursday, September 3, 2020	572.1	40	40	2.80	

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.541	3.54	8.299	8.291	76.90	78.72	2.62%	48.06	49.20	2.62%
				76.47			47.79		
3.641		8.534		81.67			51.04		
				77.49			48.43		
3.43		8.039		79.91			49.94		
				79.85			49.91		
3.103	3.26	7.273	7.648	68.36	69.91	3.85%	42.73	43.69	3.85%
				69.30			43.31		
3.368		7.894		65.94			41.21		
				70.15			43.84		
3.318		7.777		73.26			45.79		
				72.45			45.28		
2.66	2.93	6.234	6.857	60.11	60.30	0.86%	37.57	37.69	0.86%
				60.11			37.57		
3.262		7.645		60.70			37.94		
				59.90			37.44		
2.855		6.691		61.16			38.23		
				59.84			37.40		
2.532	2.51	5.934	5.875	45.78	45.07	2.97%	28.61	28.17	2.97%
				43.51			27.19		
2.549		5.974		46.83			29.27		
				43.43			27.14		
2.439		5.716		45.40			28.38		
				45.45			28.41		

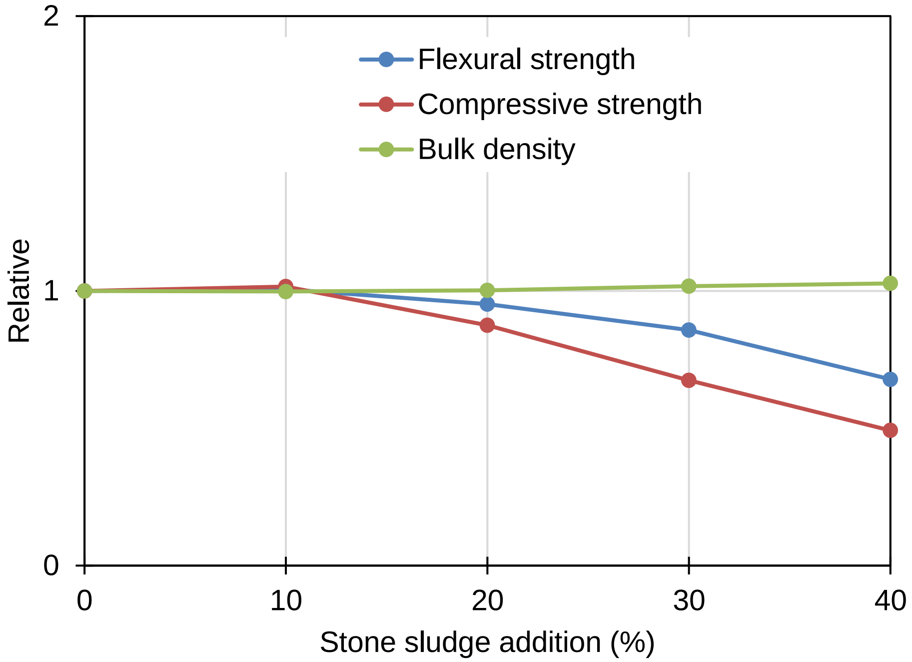
Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.095	3.17	7.254	7.423	71.40	69.31	2.18%	44.63	43.32	2.18%
				68.84			43.03		
3.275		7.676		67.26			42.04		
				69.14			43.21		
3.131		7.338		68.50			42.81		
				70.72			44.20		
3.053	3.00	7.155	7.022	58.75	59.74	1.95%	36.72	37.33	1.95%
				59.24			37.03		
2.91		6.820		58.52			36.58		
				59.57			37.23		
3.025		7.090		61.17			38.23		
				61.16			38.23		
2.625	2.70	6.152	6.322	46.43	46.06	2.96%	29.02	28.79	2.96%
				43.92			27.45		
2.745		6.434		47.17			29.48		
				44.82			28.01		
2.722		6.380		46.97			29.36		
				47.06			29.41		
2.072	2.13	4.856	5.003	34.95	33.57	3.03%	21.84	20.98	3.03%
				33.33			20.83		
2.056		4.819		32.48			20.30		
				32.75			20.47		
2.276		5.334		34.69			21.68		
				33.24			20.78		

Breaking-load in N	Average breaking-load in N	Bending tensile (flexural) strength in N/mm2	Average bending tensile (flexural) strength in N/mm2	Breaking-load in KN	Average breaking-load in KN	Breaking-load COV in %	Compressive strength in N/mm2	Average compressive strength in N/mm2	Compressive strength COV in %
3.232	3.16	7.575	7.409	70.05	70.98	1.54%	43.78	44.36	1.54%
				72.56			45.35		
3.209		7.521		70.96			44.35		
				69.54			43.46		
3.042		7.130		71.04			44.40		
				71.72			44.83		
2.582	2.49	6.052	5.829	44.43	42.61	14.48%	27.77	26.63	14.48%
				45.89			28.68		
2.238		5.245		46.16			28.85		
				30.13			18.83		
2.641		6.190		44.06			27.54		
				45.01			28.13		

At 7 days

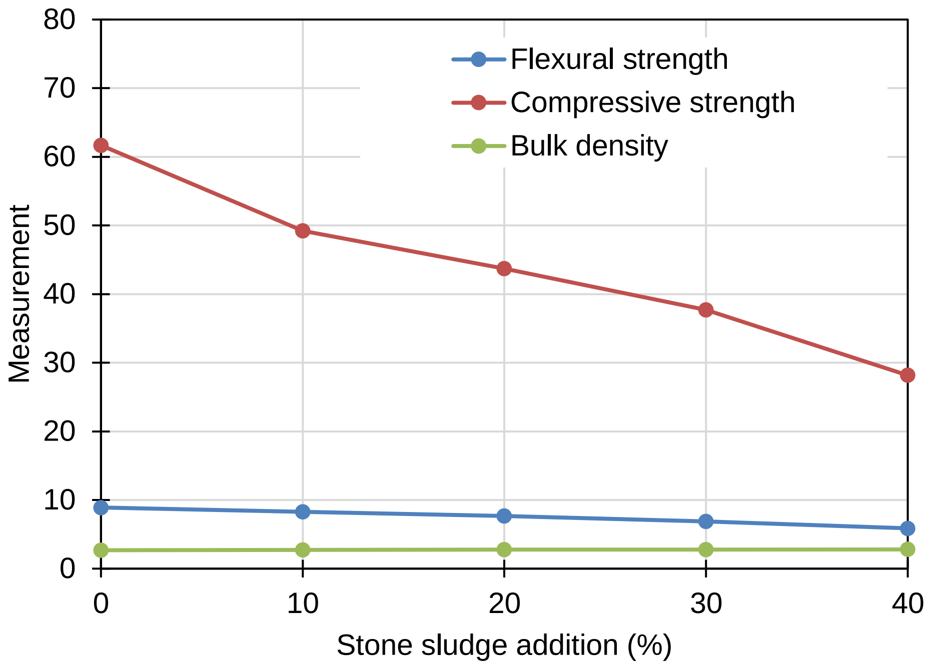


80
70
60
50
40
30
20
10
0
Measurement
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)

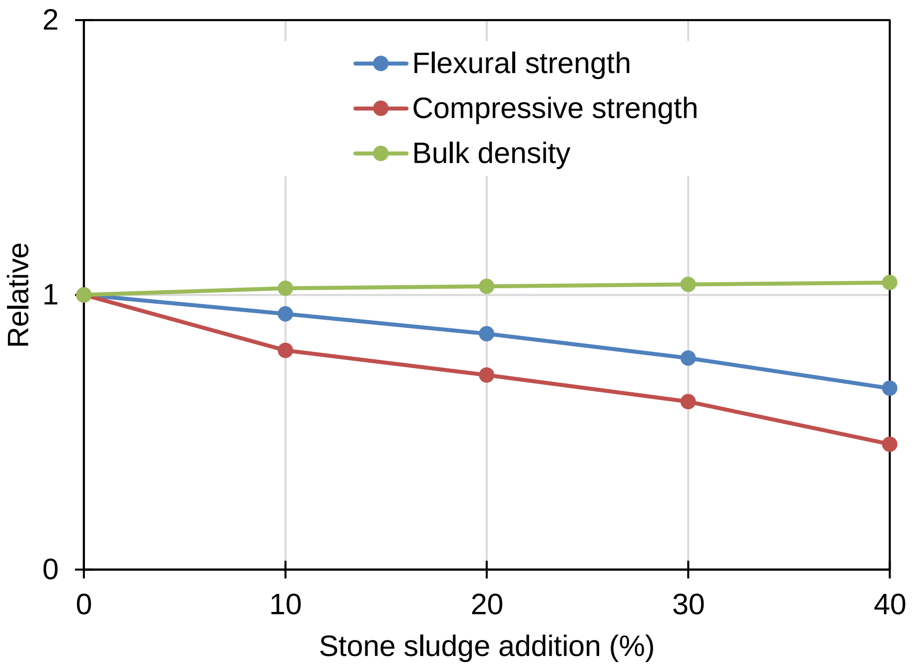


2
1
0
Relative
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)

At 28 days



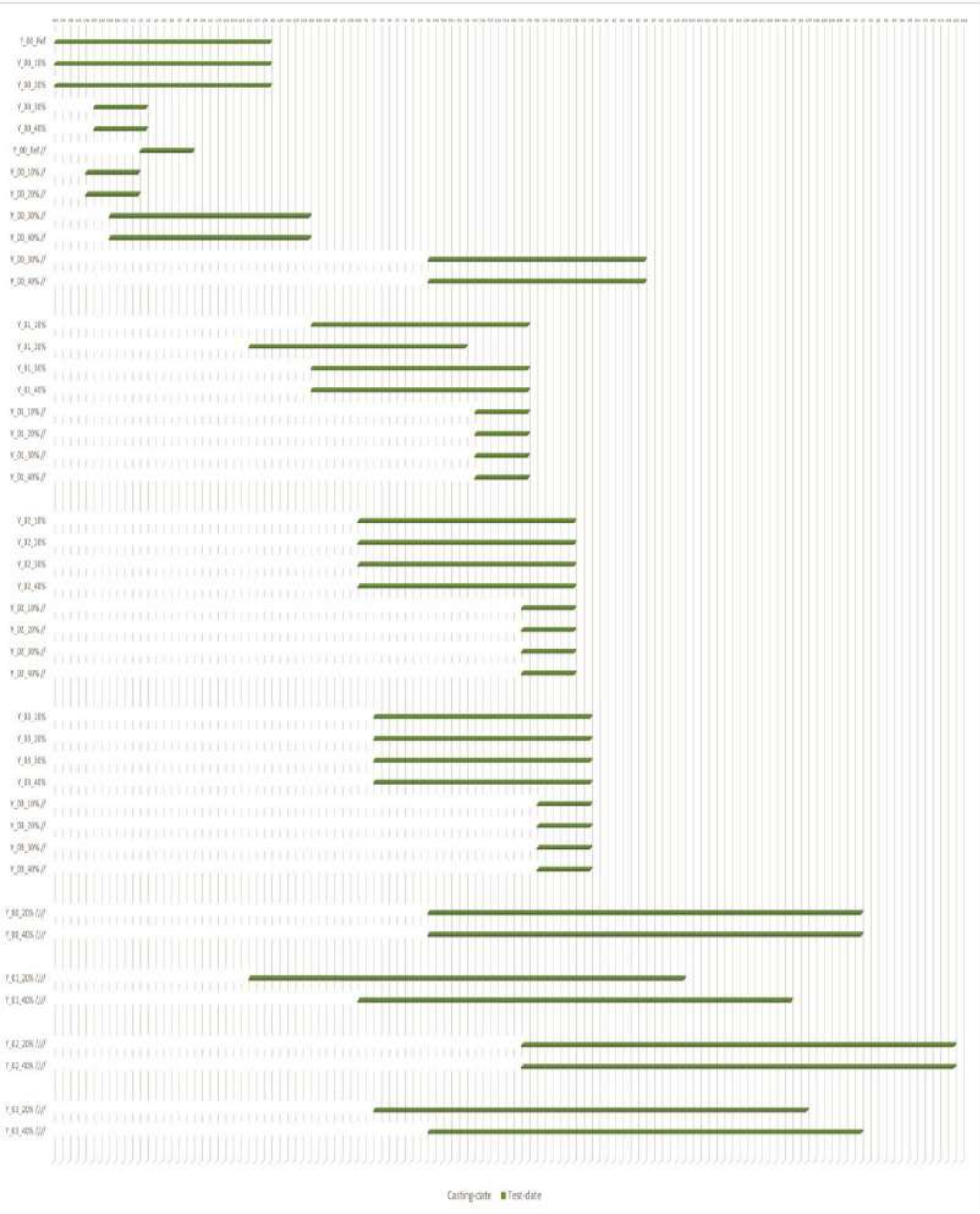
80
70
60
50
40
30
20
10
0
Measurement
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)



2
1
0
Relative
Flexural strength
Compressive strength
Bulk density
0
10
20
30
40
Stone sludge addition (%)

Appendix (V) Time-line

Specimen	Test-age	Casting-date	Test-date	Casting-time
Y_00_Ref	28	Friday, May 22, 2020	Friday, June 19, 2020	16:45
Y_00_10%	28	Friday, May 22, 2020	Friday, June 19, 2020	17:15
Y_00_20%	28	Friday, May 22, 2020	Friday, June 19, 2020	17:45
Y_00_30%	7	Wednesday, May 27, 2020	Wednesday, June 3, 2020	15:30
Y_00_40%	7	Wednesday, May 27, 2020	Wednesday, June 3, 2020	15:55
Y_00_Ref //	7	Tuesday, June 2, 2020	Tuesday, June 9, 2020	15:15
Y_00_10% //	7	Tuesday, May 26, 2020	Tuesday, June 2, 2020	15:20
Y_00_20% //	7	Tuesday, May 26, 2020	Tuesday, June 2, 2020	15:45
Y_00_30% //	26	Friday, May 29, 2020	Wednesday, June 24, 2020	16:45
Y_00_40% //	26	Friday, May 29, 2020	Wednesday, June 24, 2020	17:10
Y_00_30% //	28	Thursday, July 9, 2020	Thursday, August 6, 2020	15:45
Y_00_40% //	28	Thursday, July 9, 2020	Thursday, August 6, 2020	15:30
Y_01_10%	28	Wednesday, June 24, 2020	Wednesday, July 22, 2020	16:45
Y_01_20%	28	Tuesday, June 16, 2020	Tuesday, July 14, 2020	15:00
Y_01_30%	28	Wednesday, June 24, 2020	Wednesday, July 22, 2020	17:15
Y_01_40%	28	Wednesday, June 24, 2020	Wednesday, July 22, 2020	17:45
Y_01_10% //	7	Wednesday, July 15, 2020	Wednesday, July 22, 2020	16:15
Y_01_20% //	7	Wednesday, July 15, 2020	Wednesday, July 22, 2020	16:30
Y_01_30% //	7	Wednesday, July 15, 2020	Wednesday, July 22, 2020	16:45
Y_01_40% //	7	Wednesday, July 15, 2020	Wednesday, July 22, 2020	17:00
Y_02_10%	28	Tuesday, June 30, 2020	Tuesday, July 28, 2020	16:15
Y_02_20%	28	Tuesday, June 30, 2020	Tuesday, July 28, 2020	16:30
Y_02_30%	28	Tuesday, June 30, 2020	Tuesday, July 28, 2020	16:45
Y_02_40%	28	Tuesday, June 30, 2020	Tuesday, July 28, 2020	17:00
Y_02_10% //	7	Tuesday, July 21, 2020	Tuesday, July 28, 2020	15:30
Y_02_20% //	7	Tuesday, July 21, 2020	Tuesday, July 28, 2020	16:00
Y_02_30% //	7	Tuesday, July 21, 2020	Tuesday, July 28, 2020	16:15
Y_02_40% //	7	Tuesday, July 21, 2020	Tuesday, July 28, 2020	16:30
Y_03_10%	28	Thursday, July 2, 2020	Thursday, July 30, 2020	16:15
Y_03_20%	28	Thursday, July 2, 2020	Thursday, July 30, 2020	16:30
Y_03_30%	28	Thursday, July 2, 2020	Thursday, July 30, 2020	16:45
Y_03_40%	28	Thursday, July 2, 2020	Thursday, July 30, 2020	17:00
Y_03_10% //	7	Thursday, July 23, 2020	Thursday, July 30, 2020	15:30
Y_03_20% //	7	Thursday, July 23, 2020	Thursday, July 30, 2020	15:45
Y_03_30% //	7	Thursday, July 23, 2020	Thursday, July 30, 2020	16:00
Y_03_40% //	7	Thursday, July 23, 2020	Thursday, July 30, 2020	16:15
Y_00_20% ////	56	Thursday, July 9, 2020	Thursday, September 3, 2020	16:15
Y_00_40% ////	56	Thursday, July 9, 2020	Thursday, September 3, 2020	16:30
Y_01_20% ////	56	Tuesday, June 16, 2020	Tuesday, August 11, 2020	15:30
Y_01_40% ////	56	Tuesday, June 30, 2020	Tuesday, August 25, 2020	17:30
Y_02_20% ////	56	Tuesday, July 21, 2020	Tuesday, September 15, 2020	17:00
Y_02_40% ////	56	Tuesday, July 21, 2020	Tuesday, September 15, 2020	17:15
Y_03_20% ////	56	Thursday, July 2, 2020	Thursday, August 27, 2020	17:30
Y_03_40% ////	56	Thursday, July 9, 2020	Thursday, September 3, 2020	16:45


Casting-date
Test-date

Appendix (VI) Laser analysis

Y_00

Mess. No	Volume cc	Deviation cc	Density g/cc	Deviation g/cc
1	1.1041	-0.003	2.7239	0.0073
2	1.104	-0.0031	2.7242	0.0076
3	1.1061	-0.001	2.7192	0.0025
4	1.1065	-0.0006	2.7181	0.0015
5	1.1084	0.0013	2.7135	-0.0032
6	1.1074	0.0003	2.7159	-0.0007
7	1.1082	0.001	2.714	-0.0026
8	1.107	-0.0001	2.7169	0.0003
9	1.1093	0.0022	2.7112	-0.0054
10	1.1101	0.003	2.7093	-0.0074

Y_01

Mess. No	Volume cc	Deviation cc	Density g/cc	Deviation g/cc
1	1.0988	-0.004	2.7691	0.01
2	1.1011	-0.0017	2.7635	0.0043
3	1.1003	-0.0026	2.7656	0.0064
4	1.1024	-0.0004	2.7603	0.0011
5	1.1021	-0.0007	2.761	0.0018
6	1.1048	0.002	2.7541	-0.005
7	1.1045	0.0017	2.7549	-0.0042
8	1.105	0.0022	2.7536	-0.0056
9	1.1031	0.0003	2.7583	-0.0008
10	1.1059	0.0031	2.7513	-0.0078

Y_02

Mess. No	Volume cc	Deviation cc	Density g/cc	Deviation g/cc
1	1.1212	-0.0031	2.7365	0.0073
2	1.121	-0.0032	2.7369	0.0077
3	1.1435	0.0192	2.6832	-0.046
4	1.1202	-0.004	2.7388	0.0097
5	1.118	-0.0062	2.7442	0.015
6	1.1236	-0.0006	2.7305	0.0014
7	1.1237	-0.0005	2.7303	0.0011
8	1.1242	-0.0001	2.7292	0
9	1.1226	-0.0016	2.733	0.0038
10	1.1242	0	2.7291	-0.0001

Y_03

Mess. No	Volume cc	Deviation cc	Density g/cc	Deviation g/cc
1	1.1241	-0.0024	2.7507	0.0058
2	1.1243	-0.0022	2.7502	0.0053
3	1.1232	-0.0032	2.7527	0.0078
4	1.1246	-0.0018	2.7493	0.0044
5	1.127	0.0005	2.7436	-0.0013
6	1.1256	-0.0008	2.7469	0.002
7	1.1289	0.0024	2.739	-0.0059
8	1.1268	0.0004	2.7439	-0.001
9	1.1301	0.0036	2.736	-0.0089
10	1.1298	0.0034	2.7367	-0.0082

نبذة مختصرة

تعتبر الموارد الأرضية مهمة للغاية ويتم استخدمها في كل مكان نظرًا لانخفاض بصمتها الكربونية حيث يمكن ببساطة استخراجها من الأرض دون أي قيود علي الشحن. يعتبر الحجر من أكثر الموارد وفرة على وجه الأرض. تنتشر هذه الوفرة في الجبال في الصخور بمختلف أنواعها. إن قدرتها التنافسية مع المواد الأخرى لا يمكن إنكارها من حيث القدرة علي التغير، التنوّع، المتانة، الانبعاثية، والمسامية، والصحة و أكثر من ذلك. أدى ذلك إلى إنشاء العديد من المباني ذات الاستخدامات المعمارية المختلفة، سواء في مراحل البناء أو التشطيب، وساهمت تلك المباني بشكل كبير في إبراز العديد من الحضارات في جميع أنحاء العالم.

المنظور الرئيسي هو الخصائص الطبيعية للحجر. وبالتالي، فإن الاستغلال الأمثل يتوافق مع إمكاناتهم وإمكانياتهم في الاستخدام. تشمل أحجار الزينة الرخام والجرانيت وأنواع الحجر الأخرى المكررة. يشمل استخدام الأحجار الطبيعية الاستخراج والنقل والتصنيع (عمليات النشر والتلميع والقطع) والتقطيع والتركيب والتخلص مما يشكل عبئًا على البيئة ويسبب مشكلات صحية، بالإضافة الي القضايا الاقتصادية.

إن عملية إعادة تدوير النفايات من الصناعات العالمية مربحة للغاية. ومع ذلك، لا تزال النفايات غير مستغلة بأفضل طريقة على المستوى الصناعي والاستثماري. وبالتالي، يمكن تنفيذ مخلفات الحجر المتولدة في مركبات خرسانية بنسب مضافة مختلفة من أجل ترشيد استخدام الموارد الطبيعية.

يتمثل النهج في تكثيف الخرسانة لامتصاص نفايات الصناعات الأخرى والمنتجات الثانوية. لذلك فإن استخدام مسحوق نفايات الحجر له تأثير تآزري إيجابي على البيئة والنباتات والحيوانات بالإضافة إلى تقليل البصمة الكربونية للأسمنت نتيجة استهلاك أقل للطاقة.

إقرار

هذه الرسالة مقدمة في جامعة عين شمس وجامعة شوتجارت للحصول على درجة العمران المتكامل والتصميم المستدام. إن العمل الذي تحويه هذه الرسالة قد تم إنجازه بمعرفة الباحث سنة 2020

هذا ويقر الباحث أن العمل المقدم هو خلاصة بحثه الشخصي وأنه قد اتبع الإسلوب العلمي السليم في الإشارة إلى المواد المؤخوذه من المراجع العلمية كلٌ في مكانه في مختلف أجزاء الرسالة..

وهذا إقرار مني بذلك،،،

التوقيع:

الباحث: يوسف الشافعي

التاريخ: 11/08/2020

النفايات من صناعة الحجر كمادة مضافة للأسمنت نحو تقليل انبعاثات الكربون من الخرسانة

مقدمة للحصول على درجة الماجستير في العمران المتكامل والتصميم المستدام

أعداد: يوسف مصطفي الشافعي

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جامعة عين شمس

أ.د كارستين فالجوت
أستاذ العمارة
جامعة عين شمس

أ.د هارالد جاريشت
أستاذ الهندسة المدنية و البيئية
جامعة شتوتجارت

لجنة الحكم

أ.د. ....الممتحن الخارجي
أستاذ.............
جامعة ....

التوقيع

أ.د. ....
أستاذ.............
جامعة ....

أ.د. ....
أستاذ.............
جامعة ....

تاريخ المناقشة:..............

الدراسات العليا

ختم الإجازة

أجيزت الرسالة بتاريخ:.............

موافقة مجلس الكلية .../.../...

موافقة مجلس الجامعة .../.../...

جامعة عين شمس

جامعة شتوتجارت

11/08/2020

جامعة عين شـــــمس

جامعة شتوتجارت

النفايات من صناعة الحجر كمادة مضافة للأسمنت نحو تقليل انبعاثات الكربون من الخرسانة

رسالة مقدمة للحصول على درجة الماجستير في العمران المتكامل والتصميم المستدام

إعداد

يوسف مصطفي الشافعي

المشرفون

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11/08/2020