Sustainable Alternatives for Concrete by adding Different Types of Natural and Industrial Waste Materials

Rana Ezzdine Lakys
Australian University of Kuwait/College of Engineering, West Mishref, Kuwait
r.lakys@au.edu.kw

Mohammad Hany Yassin
Australian University of Kuwait/College of Engineering, West Mishref, Kuwait
m.yassub@au.edu.kw

Adel Jumaah
Australian University of Kuwait/College of Engineering, West Mishref, Kuwait
jumaah@auedukw.onmicrosoft.com

Abstract

The construction industry accounts for a high percentage of global energy-related CO_2 emissions (37 % in 2021 based on data from United Nations Environmental Program - UNEP) leading to an increasing need for solutions to aggressively reduce the energy demand in the built-up environment. Previous research showed that adding natural fibers such as Palm Tree Fronds (PTF) enhances the thermal behavior of concrete but may have negative effect on its mechanical properties as it may dramatically reduce its compressive strength and hence its durability. The work conducted previously by the authors confirms the research findings for different grades of concrete. Therefore, the possibility of adding another type of waste to compensate the compressive strength of concrete was explored. This additional material was chosen based on environmental consideration and the solution of adding Ceramic Waste Powder (CWP) was adopted. According to literature review, adding CWP may enhance not only the mechanical resistance of concrete but also its workability and its resistance to segregation. In this aim, different groups of mixes are performed to obtain the optimal mix for a high strength sustainable concrete: Control mix, CWP mix where CWP was added to replace 33% of the cement mass, and (CWP+PTF) mix where CWP (33% of the cement mass) and PTF (0%, 0.5% and 1% of sand volume) were added to the mix. The results of the compressive strength at early age (1 day) showed that the best results were obtained for the (CWP + PTF) mix with 0.5 % of added PTF.

Keywords: Sustainability; Concrete Mix; Palm Tree Waste; Ceramic Waste Powder; Compressive strength

1 Introduction

Concrete is the most used material in the modern built environment. The annual production of concrete is continuously increasing resulting in consuming large amounts of component materials. It is estimated that concrete production consumes around 15 billion tons of aggregates and 4.2 billion tons of cement per year according to (Langer et al., 2004).

One the greatest environmental drawbacks of concrete production is its large CO_2 footprint. On average, around 700-900 g of CO_2 is released per each kg of cement (Marincovic et al., 2010; Muller et al., 2014). Despite continued efforts to move towards renewable energy sources in the cement production process, CO_2 emissions cannot be reduced due to the unpreventable release of CO_2 during the calcination reaction in addition to the emissions resulting from transportation. Globally, the construction industry is responsible for more than 34% of energy demand and around 37% of CO_2 emissions in 2021 according to the *2022 Global Status Report for Buildings and Construction* published by the United Nations Environment Program (UNEP, 2022).

Nowadays, the topic of developing sustainable construction materials to reduce both financial and environmental load resulting from construction-related activities has become a priority for researchers. The work presented in this paper falls within this context. It aims to search for the optimal concrete mix including two types of waste: a natural (organic) waste material, the Palm Tree Fronds (PTF) fibers, and an industrial waste material, the Ceramic Waste Powder (CWP) to optimize the thermal resistance of concrete reducing the energy consumption of the built environment without compromising its mechanical properties, the compressive strength in particular. Therefore, different mixes with different percentages of added wastes are investigated in this study.

2 Background

In recent years, the research on developing sustainable concrete to address the issue of global climate change has gained increasing interest all around the world. The main focus of this research is on:

1- The reduction of cement in concrete to reduce the financial and environmental cost generated by the cement production process by partially substituting the cement with alternative natural or industrial binding materials. In most of the related research, the cement substitute assured an equivalent or even higher mechanical performance of the concrete due to its pozzolanic properties such as rice husk ash (Zareei et al., 2017), waste paper ash (Kejela, 2022), waste brick powder (Mansoor et al., 2022), silica fume (Khalid et al., 2019; Imam et al., 2018), waste glass powder (Yassen et al., 2018), fly ash (Khalid et al., 2019), ground granulated blast furnace slag (Khalid et al., 2019), ceramic waste (Raval, 2013), demolition waste (Srivastava et al., 2013), glass waste (Yaseen et al., 2018) and others.

2- Adding or partially replacing concrete natural components such as fine and coarse aggregates with natural or industrial materials. In conventional concrete, around 70% of the concrete volume consists of natural aggregates. Replacing part of these natural components helps in saving natural materials for future generations and participates in enhancing concrete properties such as the workability, the density, the thermal resistance, the flexural strength, etc. The aggregates' substitutes may consist of organic materials such as natural fibers derived from coconut shell (Gunasekaran, 2013; Kumbhar, 2018) (Sujatha & Deepa, 2020), coir, palm, kenaf, jute, sisal, banana, pine, sugarcane and bamboo (Ahamed et al., 2020) or industrial waste such as construction and demolition waste materials (Jagan, 2017) (Singh & Sancheti, 2019), waste plastic (Sharma et al., 2021), waste tyre rubber (Rohini et al. 2016), waste ceramic tiles (Sekar, 2017), recycled aggregates (Marinkovic et al., 2020) and others. Using these various natural and industrial wastes contribute not only in saving the natural sources but also in reducing the waste to be dumped and thus reducing groundwater pollution.

The use of palm tree fronds (PTF) in construction has been applied for long time especially in hot dry climate region. The concept of introducing fibers to the concrete mix was found beneficial to compensate for the weak tensile resistance of concrete, thus reinforcing fibers in concrete can minimize or eliminate the formation of shrinkage cracks (Al-Kutti, 2017; Machaka et al., 2014). In addition to its mechanical effects on the performance of concrete, previous studies showed that PTF fibers improve the overall thermal resistance of the material when added to the mix (Benmansour et al., 2014; Yassin et al., 2020). A previous study conducted by the authors investigated the effect of adding ground PTF (as replacement for sand) on the mechanical behavior of concrete (Ezzdine Lakys, 2021). The study concluded that ground PTF should be added in very low percentages (1% of sand replacement) to avoid excessive reduction in compressive strength.

Nowadays, an extremely large number of ceramic tiles is produced annually to meet the increasing need in construction as a result of the fast-growing populations. Large volumes of production inevitably result in large volumes of waste; the ceramic tiles waste resulting from construction works are estimated at 30% of total ceramic production, according to (Torkittiku & Chaipanich, 2010). This waste is generally dumped on the ground leading to environmental damage. On the other hand, adding ceramic waste powder (CWP) to concrete as a partial cement substitute was investigated by Irassar et al. (2014) and Mohit & Sharifi (2019) and many others, and it was found that the CWP enhances the hydration reaction due to its cementitious properties and reduces the alkali-silica reaction expansion resulting in a higher strength of concrete.

In this study, PTF fiber was chosen due to its ability to enhance the thermal resistance of concrete while CWP was chosen for its pozzolanic properties to increase the strength of concrete.

3 Experimental Plan

The experimental plan consisted of preparing the two type of wastes, the PTF and the CWP, in the first phase. The second phase included the concrete mix preparation: mix design for all mixes, concrete mixing and samples casting and curing. Three cylinders of 100 mm diameter and 200 mm length were cast for each mix. The final phase consisted of testing the concrete samples.

3.1 Materials Preparation

The PTF is chemically treated, then ground as explained in a previous work (Lakys, 2022). **Fig. 2** shows the particle size distribution for the ground PTF fibers, 85% of the fibers range between 0.5mm and 2 mm while 35% fall below 0.15 mm.

The CWP was obtained by crushing waste ceramic tiles in an aggregate crushing machine then by reducing the coarse particles into fine particles by placing them in a Los Angeles Abrasion for minimum 30 minutes. As a final step, the ground particles were sieved by a No. 200 sieve to obtain the powder shown in **Fig. 1**.

Fig. 1: Ceramic waste powder and PTF fibers

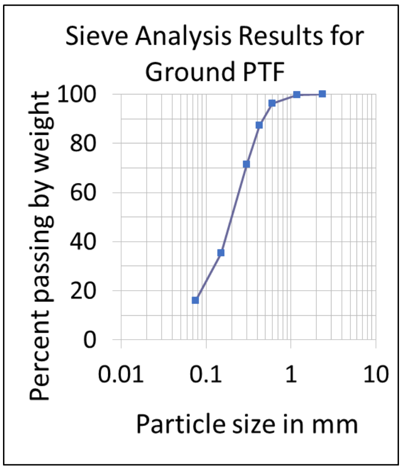

Fig. 2: PTF Sieve analysis

3.2 Mix Design

The concrete mix should be designed to ensure at the same time a great workability/fluidity of the concrete and a high resistance to segregation, which can be very challenging given that these two properties are contradictory. In a typical concrete, when the workability increases, the resistance to segregation decreases. The key factors for a successful mix design for a high strength concrete with great workability are high cementitious/fine powder dosage (450-600 kg/m3), limited aggregate content (ratio of coarse aggregate volume to total mixture volume limited to 45-48 %), low water-powder ratio (ratio of water to cementitious material limited to 0.28-0.45 %) and use of superplasticizer. Our mix design was performed based on these factors to obtain M60 grade concrete.

Five groups of mixtures (families) are cast to investigate the addition of PTF in different percentages as replacement for sand and the partial replacement of cement by ceramic powder. The families are defined as follows:

1. S0-P0: is the control mix designed with 0 % CWP and 0 % PTF;
2. S33-P0: is the mix designed with 33 % CWP and 0 % PTF;
3. S33-P0.5: is the mix designed with 33 % CWP and 0.5 % PTF;
4. S33-P1: is the mix designed with 33 % CWP and 1 % PTF;
5. S0-P1: is the mix designed with 0 % CWP and 1 PTF.

Table 1: Mix Design for all families (mixes)

<table>
<tr><th>Mix</th><th>Cement [kg]</th><th>CWP [kg]</th><th>Water [ℓ]</th><th>Aggregate (12.5 mm) [kg]</th><th>Aggregate (9.5mm) [kg]</th><th>Sand [kg]</th><th>PTF [kg]</th><th>Admixture [ℓ]</th></tr>
<tr><td>S0-P0</td><td>450</td><td>0</td><td rowspan="5">150</td><td rowspan="5">598</td><td rowspan="5">598</td><td>625</td><td>0</td><td rowspan="5">6.5</td></tr>
<tr><td>S33-P0</td><td rowspan="3">300</td><td rowspan="3">150</td><td>625</td><td>0</td></tr>
<tr><td>S33-P0.5</td><td>622</td><td>1.92</td></tr>
<tr><td>S33-P1</td><td>619</td><td>3.85</td></tr>
<tr><td>S0-P1</td><td>450</td><td>0</td><td>616</td><td>5.76</td></tr>
</table>

4 Results

The results, shown in the following sections, aim to evaluate the effect of adding the wastes with various percentages on fresh concrete, in terms of workability, and on concrete cured for one day (hardened concrete) in terms of compressive strength.

4.1 Fresh Concrete

The slump test (ASTM C143-78, 2017) was performed for all mixes. The control mix S0-P0 slumped by 50 mm (low to medium workability) while all other mixes showed a collapse slump resulting in a high workability concrete (**Fig. 3** and **Fig. 4**). Therefore, the traditional slump test was considered inappropriate for these mixes and the inverted slump test (ASTM C192–19, 2020) was performed instead. The mixes including ceramic waste powder and PTF gave similar results, the concrete flowed during 20 to 25 seconds to spread into a circle of a diameter varying from 420 mm to 500 mm. These mixes did not achieve the self-consolidating concrete condition but were very close.

Fig. 3: Slump test for S0-P0

Fig. 4: Collapse slump for S33-P0.5

4.2 Hardened Concrete

The concrete samples were cured for one day according to ASTM C192–20, 2020 and demolded and tested for compression according to ASTM C39–21, 2021. The compression test set-up is presented in Figure 5. The results of the compressive strength are given in **Table 2**. It is observed that when considered separately the effect of PTF (Mix S0-P1) and the effect of CWP (Mix S33-P0), the compressive strength decreased for both, while an increase in strength was detected for the combined effect of PTF and CWP (Mix S33-P0.5), a percentage of 1% of sand replacement by PTF resulted in reducing the concrete strength.

Replacing 33% of the weight of cement with CWP reduced the compressive strength of the concrete by 23%, similar result was found by Shaikh-ul-Karim (2020) where a reduction of 26,7% was observed due to 30% replacement of cement by CWP after 3 days of curing. Shaikh-ul-Karim (2020) found that there is no significant reduction of the strength when adding CWP as cement substitute with a limit of 20%. The results of our study show that the control mix (0% CWP and 0% PTF) and the mix S33-P0.5 (33% CWP and 0.5% PTF) have almost similar strength, around 16 MPa at Day 1. Replacing 0.5% of sand volume by PTF increased the strength of concrete after one day of curing by around 27% compared to its strength when no PTF is added (S33-P0) while replacing 1% of sand volume by PTF decreased it by around 30%.

Fig. 5: Compression test set-up

Table 2: Compression test results for all samples

Mix	Compression test results (MPa)			Average (MPa)	Standard Deviation (MPa)
S0-P0	16.60	12.67	19.01	16.09	3.20
S33-P0.5	14.4	16.25	16.42	15.69	1.12
S0-P1	11.78	10.47	16.26	12.84	3.04
S33-P0	12.47	12.2	12.47	12.38	0.16
S33-P1	11.14	10.3	11.84	11.09	0.77

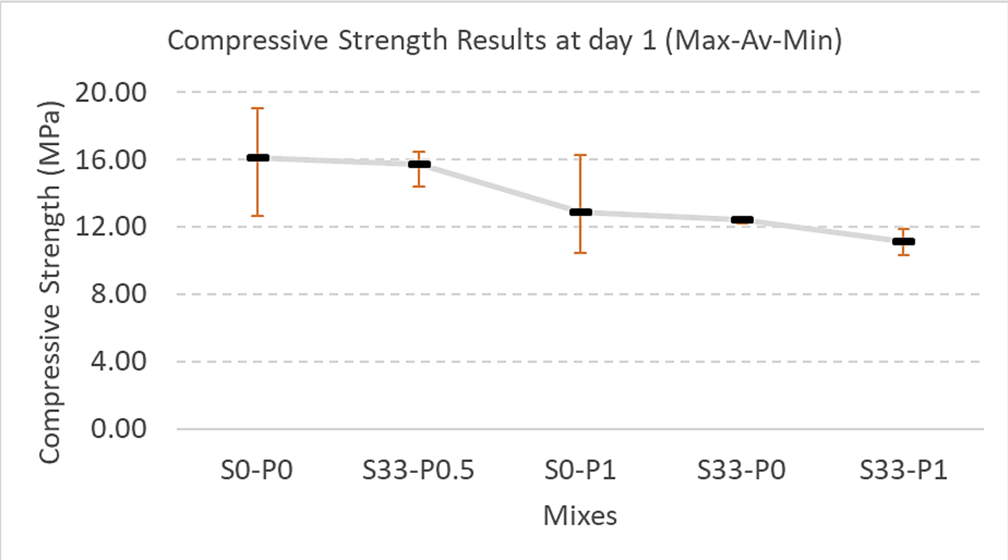

Fig. 6: Compression test results showing maximum-average-minimum values for each mix

5 Conclusion

In this study, the results of adding two types of wastes to concrete are investigated: CWP as cement substitute and PTF as sand substitute. To achieve this aim, various mixes were designed and cast. The workability of the fresh concrete was explored and three samples from each mix were tested after one day of curing to investigate the effect of the added wastes on the compressive strength of concrete. The results showed that the workability of concrete was greatly enhanced when adding the two wastes. The compression test results showed that adding one type of waste reduced the strength of concrete while no significant strength reduction was found when adding both (CWP at 33% of cement replacement and PTF at 0.5% of sand replacement). This combination was considered to be the optimal mix in terms of compressive strength when compared to others mixes. The results are promising particularly when considering that CWP may lead to higher strength after a longer curing period (more than 28 days) due to pozzolanic reactions (Mohit & Sharifi, 2019).

The results of this study represent a great significance in terms of sustainable construction since it emphasizes on the re-use of ceramic tile waste as CWP in a relatively high proportion as cement replacement (33%) with no significant reduction of compressive strength of concrete particularly when considering that the cement production accounts for 5 to 8% of global greenhouse gas emission according to (El-Dieb & Kanaan, 2018). On the other hand, incorporating the PTF in the concrete mix, even in small percentages, enhances the thermal resistance of the concrete according to a previous study conducted by the authors (Yassin, 2020) resulting in reducing the energy consumption of the construction. Further studies are needed to investigate the effect of adding these two wastes with various percentages on the concrete (flexural strength, water absorption, density, absorptivity, durability, etc.) for both short and long terms.

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