

Producing mixtures of Sustainable Recycled Aggregate Concrete to Be Used for Internal and External Artificial Cladding

Fatima Alsaleh^{*1} Feras Al adday Al khalil²

^{*1}. Professor, Faculty of Civil Engineering, University of Aleppo, Syria.

alsaleh-f@alepuniv.edu.sy

². Assistant Professor² Faculty of Civil and Architectural Engineering, University of Kalamoon, Syria .

feras.aladday@uok.edu.sy

Abstract:

One of the environmental contributions of construction engineers is the use of sustainable materials. Based on this, an experimental program is conducted to determine the effectiveness of using demolished building waste such as recycled aggregates (RA), plastic waste (PW), and textiles waste (TW) in external artificial stone wall cladding (EASWC) and internal artificial stone wall cladding (IASWC). Controlling mixtures of IASWC are prepared from fine RA, white cement, and gypsum. In addition, four types of mixtures have also been prepared, where fine RA is replaced with 5, 10, 20% of PW, and 1, 2, and 4% of TW, and proportions of gypsum to hydraulic binder (gypsum and cement) were 0.4:0.6:0.8. Several experiments are also conducted using RA from different sources (with dominant components of stone SRA, concrete CRA, and block BRA) in three mixtures of EASWC. Experiments showed that the IASWC mixture which contained 2% of TW with a ratio of 0.8 gypsum/ binder ratio, has given greater compressive and flexural strength, 12.6 MPa and 5.5 MPa respectively. The EASWC mixture containing dominant proportions of SRA has greater compressive strength. Finally, sustainable internal and external cladding can be produced from RA, PW, and TW with low cost and acceptable mechanical properties.

Keywords: Stone Wall Cladding, Recycled Clothing Waste, Recycled Stone, Sustainability

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إنتاج خلطات خرسانية مستدامة من الحصويات معادة التدوير لاستخدامها في إكساء الجدران الداخلية والخارجية

فاطمة الصالح^{1*} فراس العداي الخليل²

^{1*} أستاذ، دكتور، عميد كلية الهندسة المدنية، قسم هندسة المواصلات والنقل، جامعة حلب.

alsaleh-f@alepuniv.edu.sy

² مدرس، دكتور، جامعة القلمون الخاصة، كلية الهندسة المدنية والمعمارية، قسم الهندسة المدنية.

feras.aladday@uok.edu.sy

الملخص:

يُعتبر استخدام المواد المستدامة أحد المساهمات البيئية لمهندسي البناء. بناءً على ذلك، تم إجراء برنامج تجريبي لتحديد فعالية استخدام نفايات المباني المدمرة مثل الحصويات معادة التدوير، والنفايات البلاستيكية، ومخلفات المنسوجات في أكساء الجدران الخارجية والداخلية بالحجر الاصطناعي. تم تحضير أربعة أنواع من الخلطات لاستخدامها في الإكساء الداخلي مؤلفة من حصويات ناعمة معادة التدوير والأسمنت الأبيض والجبس، حيث يتم استبدال الحصويات معادة التدوير الناعمة بـ 5، 10، 20% من نفايات البلاستيك، و1، 2، 4% من مخلفات المنسوجات، بينما كانت نسب الجبس إلى الرابطة الهيدروليكي (الجبس /الأسمنت) كانت 0.4:0.6:0.8. أما بالنسبة للحصويات معادة التدوير الخشنة فقد تم إجراء العديد من التجارب باستخدام مصادر مختلفة حسب المكونات السائدة (الحجر، الخرسانة، البلوك) لاستخدامها في إكساء الخارجي. أظهرت التجارب أن الخلطة الخرسانية التي تحتوي على نسبة استبدال 2% من مخلفات المنسوجات وبنسبة 0.8 جيس/نسبة رابطة أعطى مقاومة ضغط ومقاومة على الشد بالانعطاف أكبر، 12.6 ميغا باسكال و5.5 ميغا باسكال على التوالي، بينما الخلطة الخرسانية التي تحوي على نسب سائدة من الحجارة المعاد تدويرها لها مقاومة ضغط أكبر. أخيراً، يمكن إنتاج حجر الإكساء الداخلي والخارجي المستدام من المواد الحصوية معادة التدوير ونفايات البلاستيك ومخلفات المنسوجات بتكلفة منخفضة وخصائص ميكانيكية مقبولة.

الكلمات المفتاحية: حصويات معادة التدوير، نفايات البلاستيك، مخلفات النسيج، مقاومة الضغط.

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سورية، يحتفظ المؤلفون

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Introduction

The increase in the demand for construction materials in recent times, and what the construction process contributes to in depleting the world's natural resources (environmental pollution) has led to the search for technological developments in the decorative stone industry, which has become a prosperous industry globally [1. Gomes et al, 2022][Metin and Tavit, 2014]. The structural elements of buildings are exposed to different environmental and climatic conditions that contribute to reducing their durability and service life. Since the cladding constitutes the external element of these elements, it is more sensitive to the impact of environmental changes in particular as it is a thin layer compared to other elements and the area exposed to environmental changes [A. Silva et al, 2013][A. Silva et al, 2011]. The service life of the external cladding of the building is very variable, depending on the type and quality of the material used, the conditions of exposure to climatic changes, the geographical location, and the performance of the users. Therefore, the service life of cladding materials varies around the world [Ferreira et al, 2022][A. Silva and J. de Brito, 2012][Silva, A et al, 2022]. From a general engineering concept, facilities are designed to protect their users from the effects of the climate, and for that, the design processes require taking into account both the climate and the selection of the appropriate construction materials [Phillipson et al, 2016]. The use of artificial stone technology helps reduce the resulting negative environmental effects compared to natural stones, these environmental changes lead to the microstructure of cladding stones (such as the mineral chemical composition of phases, open porosity, distribution of pore size, etc.), and thus the physical and mechanical properties of the stones are modified [Spagnolo et al, 2020]. Where the effective porosity increases when exposed to environmental weather factors, and in some cases, the increase reaches between 4% - 10% for some types of stones. As for the pore size distribution that is affected by weathering, the dissolution of the soluble parts leads to an increase in the pore size (larger pores are

formed due to the collapse or dissolution of smaller pores) [Franzoni et al, 2013]. Artificial stone is a technique of imitation of natural stone. The engineering term for artificial stone refers to a mixture consisting of mainly mineral raw materials up to 80%, 20% granite or marble chips, and a binder (polyester/acrylic) [F. Fatiguso et al, 2013][andriievska, 2017]. The trend towards environmentally friendly industrial stones is attributed to the availability of certain types, the cost of both quarrying equipment and transportation means for natural stones, as well as the large depletion of natural resources [Stefanidou et al, 2015]. Artificial stones have less water absorption and are non-porous, so they are superior to natural stones, and therefore they are a good choice as a building material for cladding walls or floors [Lee, et al, 2008]. In addition to the low cost related to transportation and mining and the ease of manufacturing and application of artificial stone, it is a sustainable material (less energy consumption and saving raw materials) [Stefanidou et al, 2015]. Desirable physical and mechanical features of artificial stone such as color uniformity, brightness, resistance, and soundness make it the fastest-developing material for cladding [Sameer et al, 2015]. Studies indicate that an appropriate mixture of Portland cement, a certain percentage of lightweight aggregate, makes artificial stone and a colored material composed of permanent mineral oxides subject to accelerated aging [Spagnolo et al, 2020]. The field and laboratory observations showed that the breakdown of the engineering system of stone cladding is primarily due to the failure of the cladding joints (45%), low stone resistance (40%), and water leakage (15%). The reduction in strength due to weathering is a real problem. Moreover, some failures in the connections can also be explained by the loss of strength of the cladding stone at the connection points [Megan & Henrique, 2016]. But, with the great developments in the industry during the end of the 19th century and the beginning of the 21st century, novel synthetic materials with certain beautiful and technological properties (increased workability, resistance of chemical and mechanical

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stresses, and flexibility) have been presented into the artificial stone industry [Salamon et al, 2021]. One promising solution is the mass fabrication of artificial stones that have replaced old-style stones [Ersen et al, 2010]. Thus, the maximum spread of the application and architectural appearance of artificial stone in all countries of Europe was reached at the beginning of the twentieth century [Yves et al, 2015][J. Griffiths, 1985].

Most of the vital activities associated with the human race are characterized by the production of quantities of waste, where waste is defined in a simplified term as something that the person disposes of. The average rate of waste production has been a real concern throughout the ages. Moreover, the increased rate of waste production recently has become a serious environmental problem. Some studies indicate that the diversity of waste increases with the increase in the volume of waste [Dadzie et al, 2020]. Global estimates and statistics indicate that a huge amount of solid waste results from the demolition of infrastructure, China is the country that produces more demolition waste, it has reached 2.36 billion tons, the US generates 600 million tons, and India 530 million tons. In the UK produced about 67.8 million tons of demolition waste, while the European Union produced a large amount of demolition waste. Germany and France were the largest producers of demolition waste. France generate 240 million tons and Germany generate 225 million tons. Generally, the bulk of it is disposed of in landfills. Thus, more technologies that are rational have become a required and effective option such as recycling and reusing demolition waste. Several studies have shown that the use of RC can decrease about 65% of greenhouse gas emissions and reduce about 58% of energy consumption compared to the natural aggregate [Liang et al, 2022][Al adday et al, 2021][Ataria et al, 2022]. Moreover, the use of natural aggregates in the preparation of concrete mixtures leads to a depletion of the natural resources of aggregates by 20 billion tons annually, and the processes of extraction, crushing, and transportation of natural aggregates lead to an increase in both CO₂ emissions and significant energy consumption [Zhang et al, 2022 [K.M.Liew et al, 2022][Al Adday et al, 2019]. Since artificial stone is a sustainable option, as mentioned earlier, the use of RC in the production process of these stones is an important factor in sustainability.

The other solid waste used in this research is PW, where PW is considered one of the serious problems around the world. Plastic becomes waste when it is

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not used again. There are two ways to get rid of PW, the first is landfill, which is a management process of PW used by most countries in the world, and the second is recycling, which involves reusing PW as secondary raw materials. It is estimated that only 21% of PW is recovered (12% incineration and 9 recycled) and the rest is buried in landfills [Chen et al, 2021]. There is an increasing global demand for plastic, as production quantities have reached 368 million metric tons annually, about 50% of plastic products are single-use, such as bags, food packaging, and water, yogurt, and milk bottles. While 20 and 25% of plastics remain for a long time in infrastructure such as plastic pipes, electrical wire covers, and construction materials. [chi Xu et al, 2021][Al Adday, 2018]. The massive consumption of plastic in China has led to more than 30 million tons of PW annually in recent years. In the US 35,370 tons of plastic were produced in 2017, and only 8.4% was recycled [Shenghua and Montalvo, 2021]. In Australia, plastic production in 2017-2018 was about 3,4 million tons, with only 9% recycled [Mashaan et al, 2021].

The last waste that was used in this research is TW, where clothes and textiles constitute a necessity, comfort, and well-being for humans, and with the developments of modern fashion since the beginning of the last century, the production quantities of clothes and textiles increased, which was followed by a significant increase in the rate of textile waste. This waste is a mixture of artificial polymeric and natural materials, which are nylon, polypropylene, polyester, woolen textiles, cotton others. It is a cause of real concern due to the increasing amounts of old clothing in landfills. According to 2018 statistics in the US, the TW constituted 5.8% of the entire landfilled solid waste, which amounted to about 17 million tons [v et al , 2022]. In the European Union, TW amounts to about 5.8 million tons per year, only 25% is recovered and 75% of the remaining TW is disposed into burned or landfills. Therefore, the problem of disposal of this waste has become a common problem that needs more creative initiatives to address the increasing and growing environmental damage in landfills [Rapsikevičienė et al ,2019]. Although the annual production rate of TW is small compared to other solid waste, it has a significant negative impact on the environment [Santos et al, 202]. Two types of TW can be differentiated. The first is waste of post-industrial, which refers to the waste produced during the industrial process of apparel, and textile (rejected quality, remains of cutting parts, rejected quality). The second type is TW products that are disposed of

because the textile owner no longer needs them [Sinha et al, 2021]. In general, textiles use the synthetic dye that this industry mainly needs. Synthetic dye is distinguished from natural ones in that they are more effective and stable to temperature and sunshine, detergents, and bacterial attack. The main environmental problem associated with the use of dyes is their loss during the dyeing process of textiles with fixation efficiency ranging from 60 to 90%. 15% of the world's total production of dyes is lost during the dyeing process and excreted into wastewater [El-Kassas, Mohamed, 2014].

1. Literature Review

Through the reference study completed for this research, there are some researches have dedicated to developing the production of artificial stones. Among them, that is done by [Ming-Yu Lee et al, 2008], they adopted the principle of using the recycled materials such as waste glass from old windows (which were crushed into powder) and recycled granite parts (from 4 mm to 0.6 mm) used as raw materials to prepare artificial stone slabs. The percentage of fine materials of granite aggregates was 60% and waste glass was 40%, with 8% unsaturated polymer resin as a binder. These materials were placed in a metal mold was exposed to heating and pressure in addition to vibration. Artificial stones were with a lower value of water absorption (0.02%), a density value of 2.44, and a high value of compressive strength and bending strength of 148 MPa, 51.1 MPa, respectively. This study concluded that the artificial stone slab has higher specifications than the natural stone slab in terms of water absorption and strength [Lee et al, 2008]. Another study for manufacturing a type of artificial stone was carried out by [S. Hamoush et al, 2011], they produced the artificial stones which consist of two layers. The first one consisting of soft, durable, strong, and colored materials to give the appearance of a natural stone called the face layer was studied, the materials that are used in face layer are a powder of calcium carbonate, limestone, and fine silica, a clay, unsaturated polyester resin and favorite dye. While the second layer is the back layer, using recycled rubber crumbs to give features such as low thermal conductivity and weight as well

as high impact resistance in addition to use the powder of calcium carbonate and perlite. This study proved that the artificial stone have a low density of 1.45 g/cm^3 compare to natural stone ranges (2.8 and 3.5 g/cm^3). The surface layer also has a high resistance of 97 MPa and low heat conductivity, $3.5 \text{ W/m } ^\circ\text{C}$ for the face layers compare to natural stone of $5 \text{ W/m } ^\circ\text{C}$. Also, the face layer of artificial stone has the absorption rate of 0.21%, compared to %8 for clay brick [Sameer et al, 2011].

[C. E. Gomes Ribeiro et al, 2014] presented their study on the possibility of producing an artificial stone from the remains of marble and liquid polymeric resins. Marble residues with sizes ranging between 0.05 and 2 mm were placed in a hot mold ($60 \text{ }^\circ\text{C}$), which represented 85% of the total volume. And then 15% of the liquid polyester resin was injected into the mold under vibration for 10 minutes. This study concluded that the artificial stone made of resin and the remnants of marble had a lower value of mechanical strength and relatively higher value for each a porosity and water absorption compared to normal artificial stone. But this mixture can be used as a suitable material for wall cladding tiles with the feature of sound and thermal insulation [Ribeiro et al, 2014]. Another group of researchers [Gomes, M.L.P.M et al, 2022] conducted a research to produce artificial stones consisting of three materials, the first is ornamental stone waste (granite waste) and constitutes 85% by total weight, the second is a vegetable polyurethane from castor oil and the third is biodegradable resin. These materials are to be placed in a metal mold subjected to heating and pressure in addition to vibration with extraction of air and moisture. The artificial stone has low water absorption and porosity in addition to a satisfactory flexural strength (17.31 MPa) compared to ordinary granite stones. Artificial stones are considered to be high strength when their flexural strength is within 16-20 MPa and very high strength when it is more than 20 MPa. And it is a good feature of the artificial stone to have a low water absorption rate when being in constant contact with water [Gomes et al, 2022].

Based on the widely available local materials and the reference literature study, the aim of this research using demolished building waste such as the

RA, PW, TW in EASWC and IASWC with adding the gypsum or white cement as hydraulic binder, which is a new technique to introduce these materials in the artificial stone industry.

2. Materials and Methods

The work methodology was divided into three main stage. Preparation of the RA was the first stage, which comprised confirming the materials suitability to be added to EASWC and IASWC mixtures, the properties of coarse RA were determined as shown in table 1. The values of L. A. abrasion and water absorption are greater than the accepted standard values. Greater values can be attributed to old mortar, which covered RA. The second stage is the preparation of the IASWC mixtures, where the reference samples were prepared according to the following ratios: 60% sand, 40% gypsum and white cement, gypsum to hydraulic binder (gypsum and cement) were 0.4:0.6:0.8, the ratio of water to the hydraulic binder was as follows: 0.75, 0.85 and 0.95% respectively. The first mixture was a ratio of gypsum to a hydraulic binder of 0.4, where fine RA is replaced with 5, 10, 20% of PW, and 1, 2, and 4% of TW. The second mixture had a ratio of gypsum to a hydraulic binder of 0.6, while third mixture had a ratio of gypsum to a hydraulic binder of 0.8. The third stage, several experiments were carried out on special mixtures for EASWC, where the cement available in local industry is used, the type of Aljamal 42.5, and the use of aggregate gradation (the traditional maximum). The use of coarse aggregate in three types according to the nature of the demolished buildings from which the recycled aggregate is taken: stone, concrete and block aggregates. Figure 1 shows the types of artificial stones that were processed in this study.



Figure (1) specimens and the types of EASWC and IASWC

Table (1) properties of coarse RA

Test	RA	Standard Specifications
L. A. Abrasion Test Mass Loss, (ASTM C131 – 63)	39.1 %	15 - 30 % Max [Kumar et al, 2013]
Specific Gravity, (ASTM C127 -07)	2.1	2.4 - 2.9 [salehlamein et al ,2015]
Water Absorption, ASTM C127 - 07)	11.6 %	0.8 – 3.7% Max [salehlamein et al ,2015]

3. Results and Discussion

In the first part of the discussion will focus on the IASWC, the relationship between replacement ratio of PW/TW and the compressive and flexural strength concrete will be shown. Figure 2 shows that the compressive strength for mixtures which contain 0.8 gypsum / hydraulic binder increase as PW replacement rate increase up to 10 % of total weight of fine RC, after this value the compressive strength decrease. It can be seen that the greatest value was at 12.5% of PW. While the rest of the proportions (0.4 and 0.6 gypsum / hydraulic binder) are decreasing with increasing PW.

As for the mixtures that contain the TW as a replacement ratio, it behaves almost the same the PW behavior as presented in Figure 3, and it can be noted that the highest value of the compressive strength (12.2 MPa) is at 0.8 gypsum / hydraulic binder with a replacement ratio of 2% of TW. In both PW and TW, the compressive strength is very close. As shown in Figure 4 and 5, the flexural strength at 0.8 gypsum / hydraulic has the highest value for 10 % and 2% for both PW and TW respectively, while the other percentages of replacement (0.4 and 0.6 gypsum / hydraulic binder) have little effect on the flexural strength. There is a clear preference for replac-

ing the TW with fine RA, as the flexural strength was 5.5 MPa at 2% of the TW, while the flexural strength for the PW did not exceed 2.3 MPa. As the standard average flexural strength is 3.7 MPa [Spagnolo at al. 2020].

With regard to the EASWC, three different types of RA were used. Figure 6 shows that the concrete mixtures containing recycled stones have the greatest compressive strength, the increase in compressive strength was 53% for recycled concrete and recycled block was 146%. Also, in this research, the moisture

absorption ratios of all samples were measured according to the percentages of PW and TW replacement exposed in the research methodology. Figure 7 shows the relationship of the percentage of moisture absorption with time for all mixtures.

The general curve was drawn for each mixture, and it was concluded that the relationship had the following formula: $y = ae^{bx}$, where: y is the percentage of moisture absorption, x is the time in days, and a, b are constants. Referring to the equations of the moisture absorption ratio diagrams, the following equation can be developed: $y = 23.378e^{0.00372x}$.

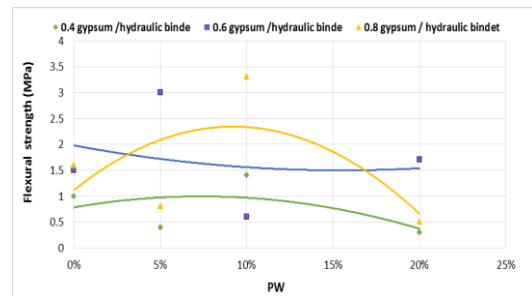


Figure (4) Represents the flexural strength of mixtures containing a PW

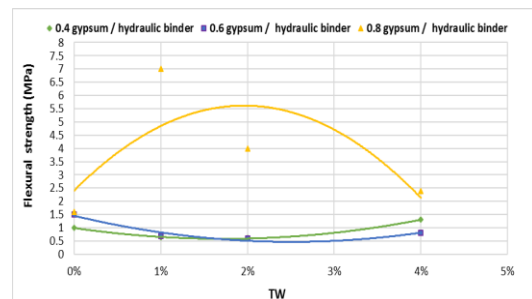


Figure (5) Represents the flexural strength of mixtures containing a TW

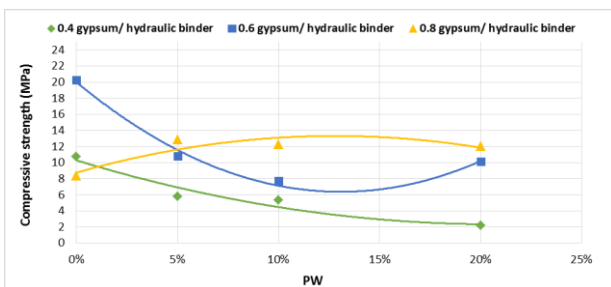


Figure (2) Represents the compressive strength of mixtures containing a PW

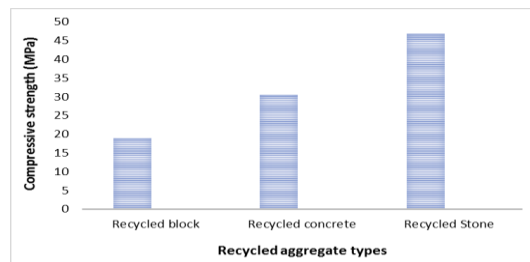


Figure (6) Compressive strength of EASWC mixtures containing recycled aggregate types

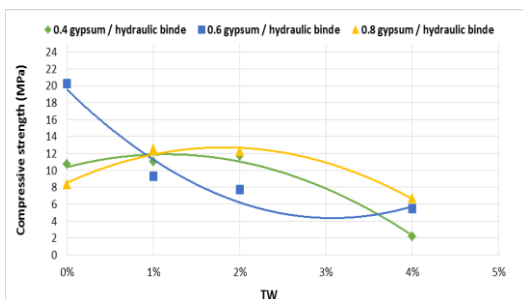


Figure (3) Represents the compressive strength of mixtures containing a TW

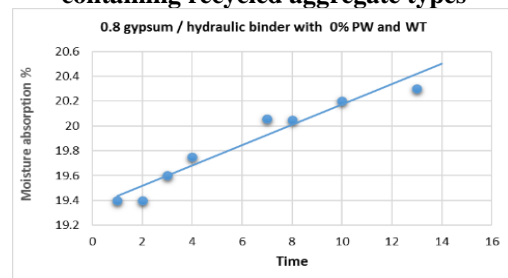


Figure (7,a) Represents the moisture absorption with time for 0.8 gypsum/hydraulic (0%WP and 0%WT)

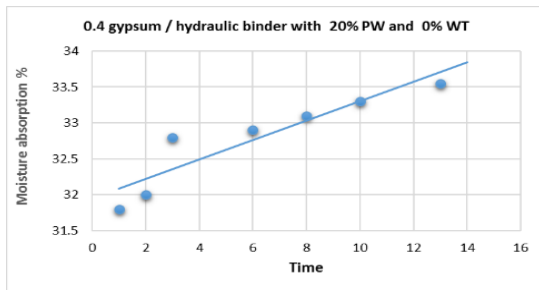


Figure (7,b) Represents the moisture absorption with time for 0.4 gypsum/hydraulic (20% WP and 0% WT)

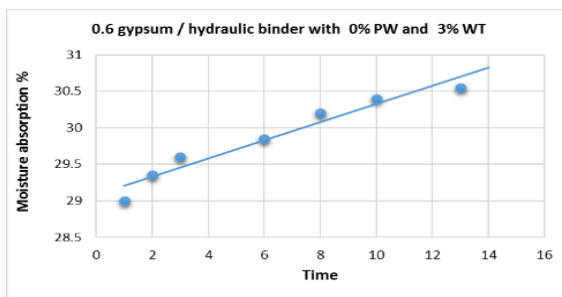


Figure (7,c) Represents the moisture absorption with time for 0.6 gypsum/hydraulic (0% WP and 3% WT)

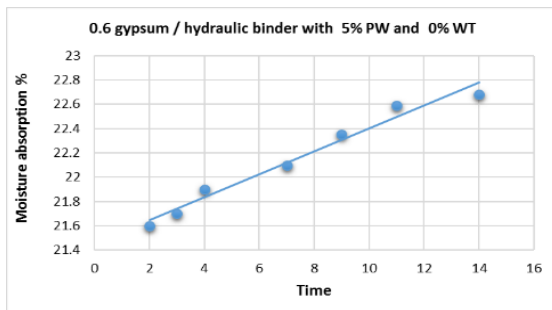


Figure (7,d) Represents the moisture absorption with time for 0.6 gypsum/hydraulic (5% WP and 0% WT)

4. Conclusions

Based on the previous experimental results, the conclusions were originated as followed:

- [1] Artificial stone for interior and exterior cladding can be produced from recycled sand and aggregates. The optimum ratios of the hydraulic binder are 0.8 gypsum / hydraulic binder with 10% of PW or 2% of WT, which has the highest compressive strength.
- [2] There is a clear increase in flexural strength when replacing TW with fine RA, where the bending strength was 5.5 MPa at 2% of TW, while the flexural strength for PW did not exceed 2.3 MPa.

[3] Concrete mixtures comprising recycled stone had the highest compressive strength concrete, and the increase in compressive strength was 53% related to recycled concrete and 146% related to recycled block.

[4] Environmentally friendly interior and exterior cladding can be manufactured from RA, PW and TW with low economic cost and acceptable mechanical and physical properties

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