



Effect of Silica Powder on the Bond between Building Stones and Pumice Concrete

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Abstract

The Concrete Backed Stone (CBS) masonry structures are common in many countries in the Middle East. The weak bond and heavyweight are two main problems facing such masonry structures. In this research, Pumice Lightweight Aggregate Concrete (PLWAC) containing silica powder addition is used in backing building stones. The main objective of this research is to investigate the effect of using silica powder addition on the bond strength between building stones and the PLWAC. An experimental program is conducted to investigate the bond strength by applying a direct shear load to the concrete-stone interface. The study investigated the effect of some parameters such as the silica content, the stone surface roughness, and the concrete strength on the bond between lightweight concrete and building stones. The stone roughness comprised specimens of saw-cut and grooved stones with different groove depths. Tests showed that the bond and the compressive strength of the PLWAC increased by increasing the silica content up to 15 percent, where they start to decline. The increase in bond strength corresponding to 10 and 15 percent silica content was 14 and 33 percent, respectively. Increasing the stone roughness by about 50 percent of the saw-cut surface area provided a full bond between the building stones and their backing concrete. Furthermore, the study offered a formula that estimates the bond strength and agrees well with test results.

Keywords: Bond Strength; Pumice Concrete; Building Stones; Masonry Structures; Lightweight Aggregates Concrete.

1. Introduction

Stone-masonry structures are widespread in many countries. The two main methods used in building masonry structures are the concrete backed stones (CBS) method and the wall tiling method. In the wall tiling, a concrete wall is constructed and then tiled by 3 to 4cm thick dressed building stones using concrete grout or using steel anchors driven into the wall. In the concrete backed stones method, shown in Figure 1, two to three courses of dressed building stones are built using flush mortar. Wood formwork or a hollow block wall is erected behind the stone courses leaving, 10 to 15 cm space filled by concrete grout. The structures built using the CBS method encounter two main problems. The first is the heavyweight of the CBS masonry structures, while the second is the weak bond between stones and the backing concrete, especially for the saw cut stones. In this study, lightweight aggregate concrete (LWAC) is used to reduce the heavyweight of concrete and accordingly lowers the structural component dimensions such as columns and foundations. Among the common types of aggregates, pumice (porous volcanic) aggregates are used as it has a unit weight ranging from 850 to 1850 kg/m³ [1] that yields LWAC mixes of dry densities ranging from 1200 to 1850 kg/m³ [1-2].

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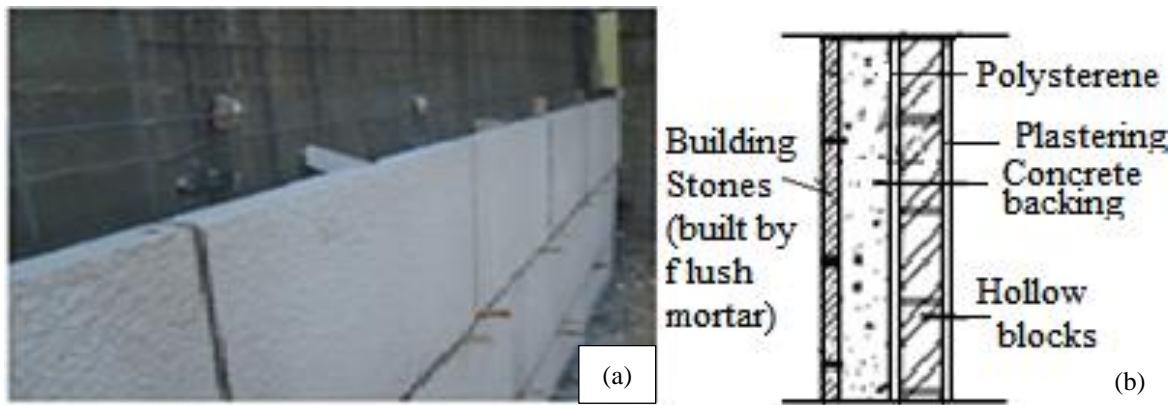


Figure 1. Method of stone backed concrete: a) Wall tiling method; b) Wall details of concrete backed stones

Generally, the decrease in concrete unit weight comes with a reduction in its strength. Silica powder is added to concrete mixes as a partial replacement of cement to compensate for the strength reduction. Furthermore, the silica addition improves workability and reduces concrete microcracks [3].

Many researchers investigated the effect of adding silica powder or silica fume to enhance concrete properties. Rjoub and Awwad [4] tested the influence of adding silica powder on the mechanical properties of concrete. The study showed that the optimum percentage of silica content was about 15 percent. Meyyapan et al [5] investigated the effect of silica fume and pumice stones in developing lightweight concrete. The study concluded that the addition of silica acts as a filler for the micropores or microcracks of concrete, and the addition of 5 percent silica fume increased the compressive and tensile strengths around 5 to 7 percent. Chaudhary and Sinha [6] find that silica fume proved very effective in improving the microstructure of concrete due to the particle fineness. They concluded that the addition of silica fume as 10 percent of cement weight reduces the water permeability by about 87 percent. Srivastava et al [7] reported that the inclusion of silica fume in the range of 5 to 25% increases compressive strength from 6% to 30% when water to cementitious material ranged from 0.25 to 0.45. The study concluded that the fine silica powder acts as a filler in concrete mixes and enables the powder to fill the space between cement particles. Imam et al [8] reviewed the effect of silica fume on concrete properties. The study found that the optimum content was about 8 to 10 percent for the compressive strength and 12 to 15 percent for split tensile strength. Kranthi et al. (2020) and Kumar and Dhaka (2016) [9, 10] studied the effect of silica fume as a partial replacement of cement on the properties of the compressive strength of concrete. Their test investigations indicated that the use of silica fume in concrete increased the strength. The addition of silica in the form of nano silica increases the bond strength of concrete and steel bars [11]

The bond strength between concrete and building stones or between old and new concretes is evaluated by applying shear stresses to the interface between concrete and building stones or between old and new concretes [12-13]. Rjoub (2005) and Bingöl and Gül (2009) [13, 14] investigated the bond between normal-weight concrete and building stones. Both studies concluded that increasing the stone roughness or improving the concrete strength increases the bond strength between concrete and building stones.

The current research replaced the normal-weight concrete by LWAC in backing the building stones. The study aimed to study the bond between building stones and the pumice lightweight aggregate concrete (PLWAC). The study has two main objectives. The first is to investigate the effect of stone roughness on the bond between the building stones and the PLWAC. And the second is to examine the influence of silica powder content in improving the bond strength between building stones and PLWAC. The following flowchart (Figure 2) summarizes the steps of research methodology.

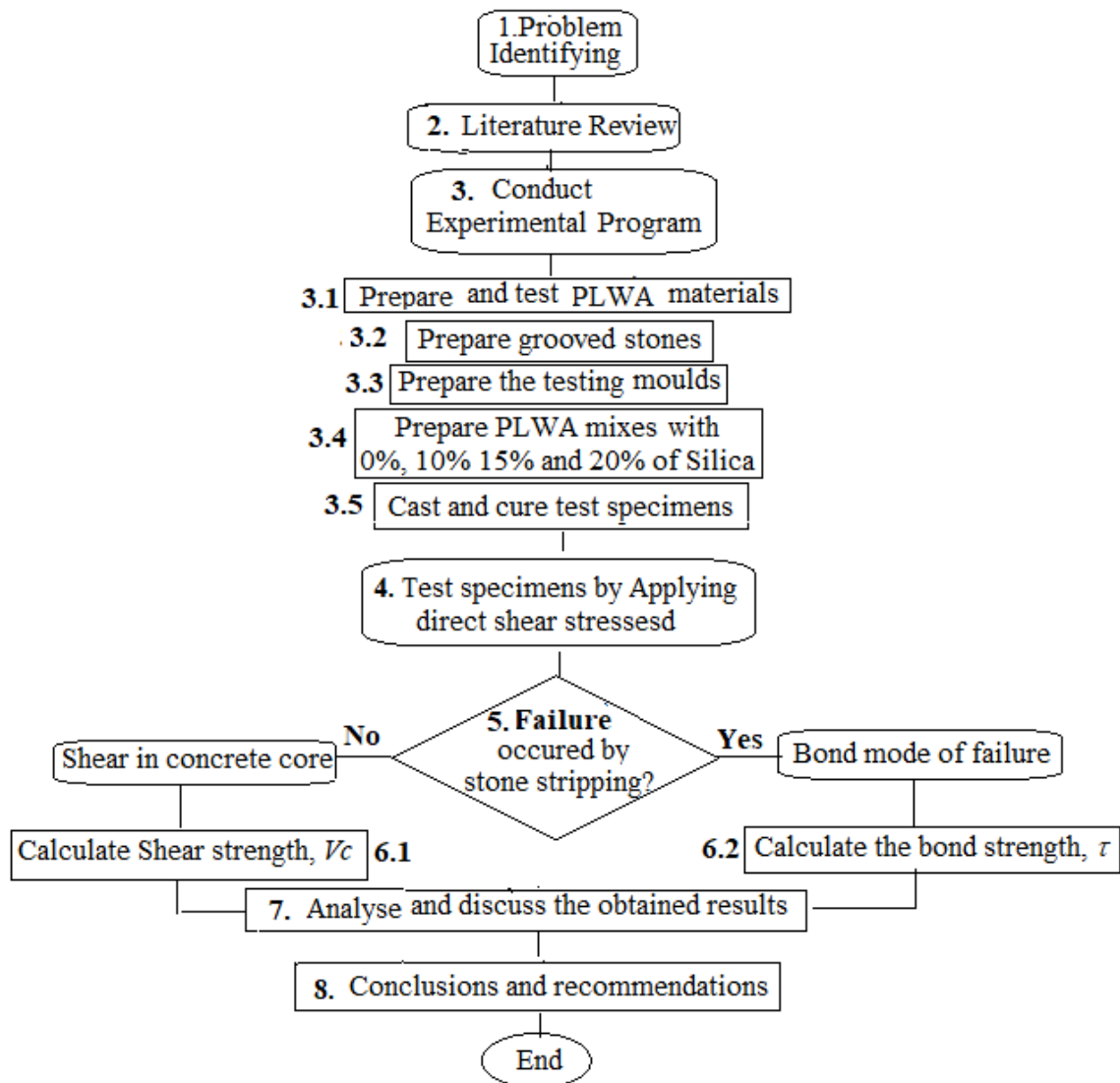


Figure 2. Steps of research methodology

2. Experimental Program

The experimental program involved testing forty concrete backed stone specimens. The stone's roughness is conducted by grooving the stone surfaces by three grooves with different groove depths as shown in Figure 3a. The groove depths were 2.5, 5, 10 and 20 mm in addition to the no-groove (saw cut) stones. Specimen molds were constructed by laying two opposite wood sides on a wood-base, and the building stones formed the other mold sides as shown in Figure 3b. The PLWAC ingredients were mixed in a rotating mixer. The mix was poured into the molds and compacted using 16 mm steel rods. The specimens were demolded after 24 hours of casting. Each cast specimen is halved into two of 145×125×40 mm (Figures 4a and 4b) and immersed in a water bath for 28 days. A universal testing machine is used in applying direct shear stresses to the stone concrete interface as shown in Figure 4d.

2.1. Materials

The chosen building stones were of limestone of sedimentary origin. The specific gravity and absorption of the building stones were obtained according to the ASTM C97 [15] and found 2.39 and 3.42%, respectively. The average compressive strength of the building stones for three 50mm cubes were tested according to the ASTM C170 [16] and found 53.2 MPa.

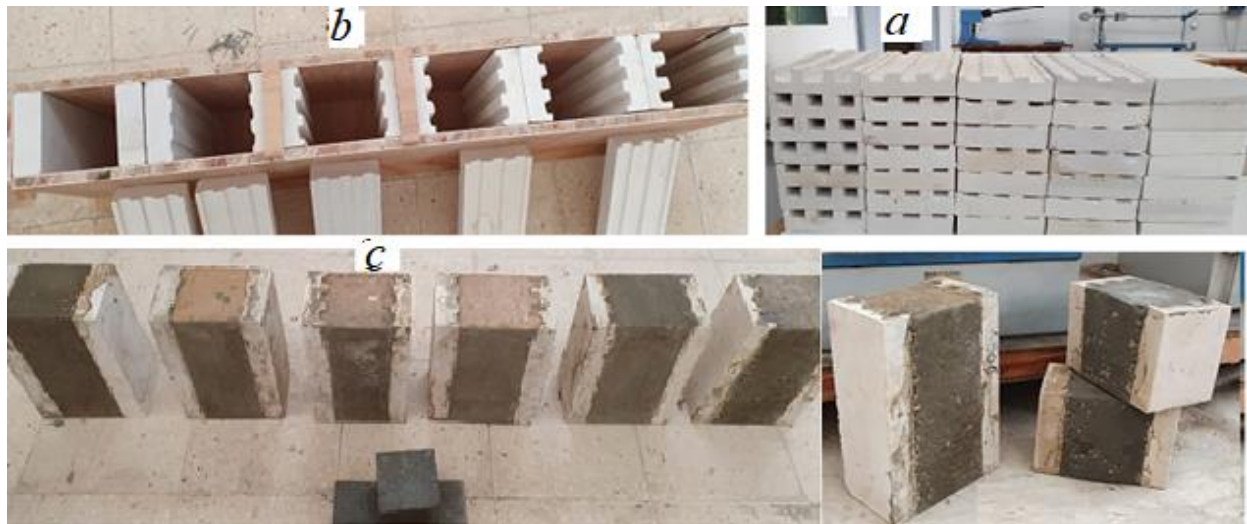


Figure 3. Experimental program: a) Grooved stones in a wood mold; b) Sample of demolded sample after casting; c) Group of grooved stones

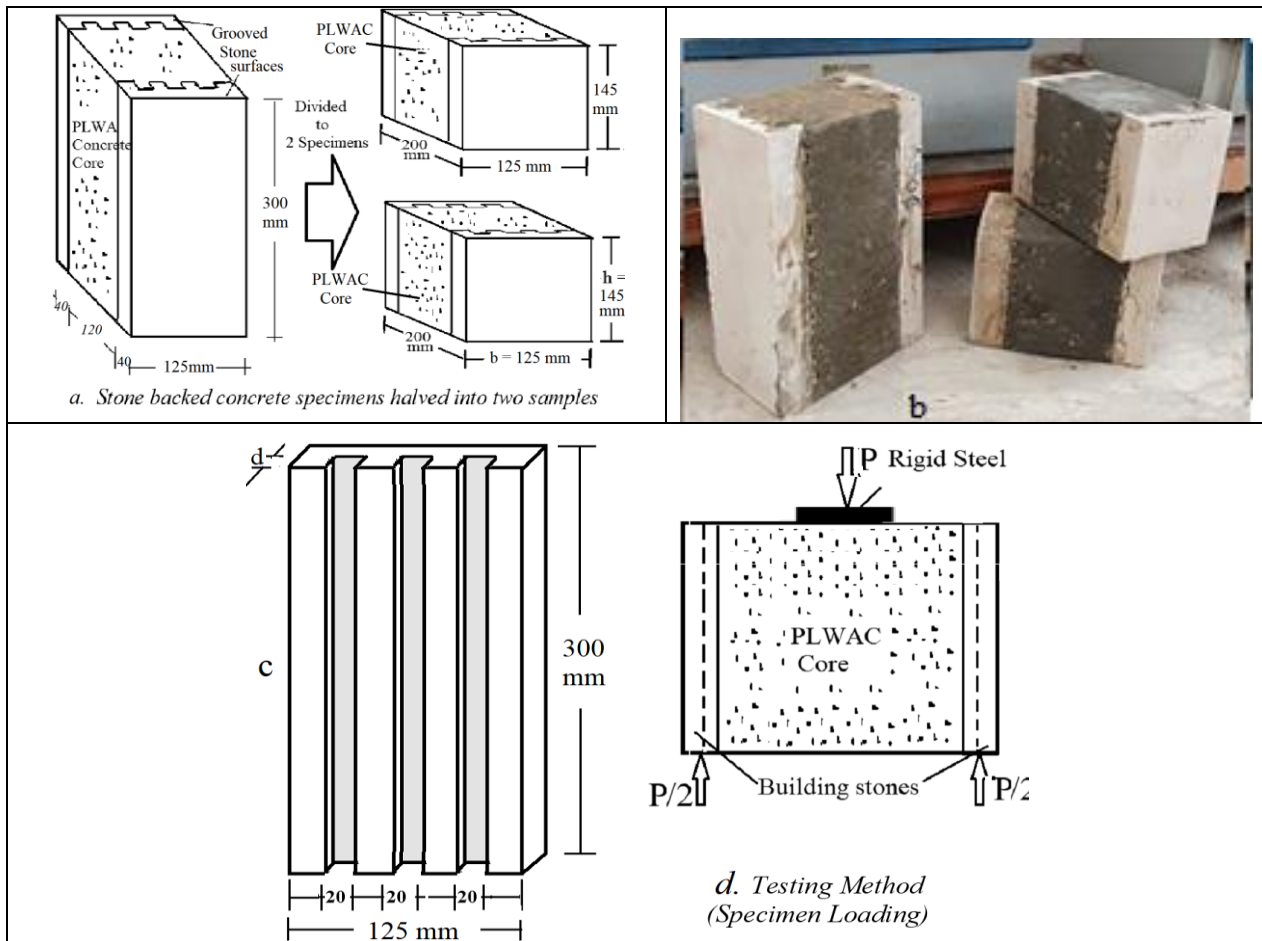


Figure 4. Test specimens and details: a) Concrete backed stone specimen and dimensions after halving; b) Cast specimen before and after halving; c) Grooving stone Surfaces. d. Testing method

2.2. Pumice Light Weight Aggregate Concrete, PLWAC

Pumice Lightweight aggregate concrete is a lightweight aggregate concrete (PLWAC) made from normal Portland cement and porous volcanic pumice of 13mm maximum aggregate size. The properties and mix proportions were obtained and listed in Table 1.

Table 1. Material properties

Properties of building stones		
Specific Gravity (ASTM C97)	=	2.39
Absorption (ASTM C97)	=	3.42%
Compressive strength, (ASTM C 170) for cubes: 50×50×50 mm,	f_{stone} =	53.2 MPa
Proportions of Pumice LWAC mix		
Fine Aggregates: (Sand 93 kg + Pumice 287 kg)	=	380 kg
Coarse Aggregates: (Pumice)	=	785 kg
Cement	=	180 kg

- The added silica replaced similar weight of cement.
- The concrete unit weight, $w_c = 1402 \text{ kg/m}^3$
- Water to cementing materials ratio, $W/(C+P) = 0.65$

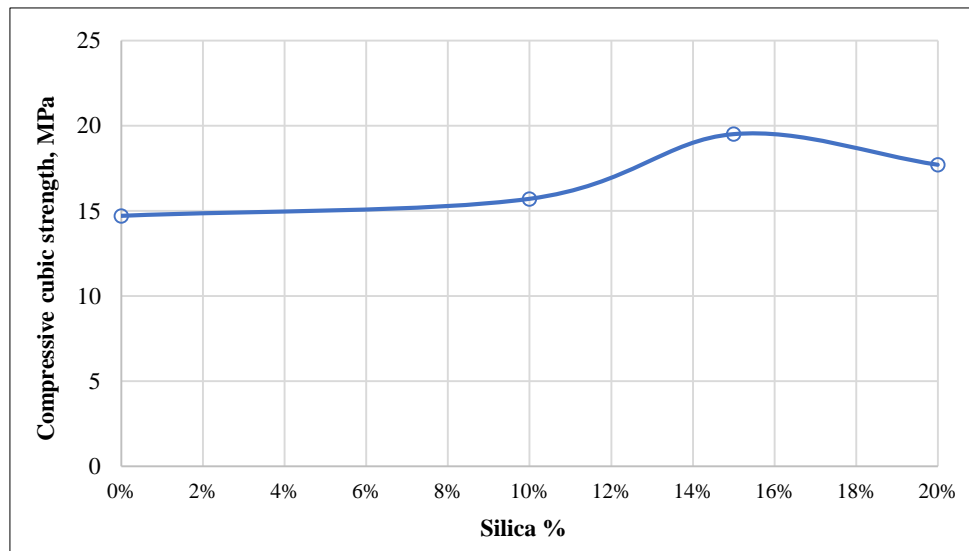
The compressive strengths of the PLWAC mixes were obtained by testing 150 mm cubes for different silica powder contents. Test results were listed in Table 2 and plotted in Figure 5. The plot shows that the optimum silica content was around 15% of cement weight. This result agrees with the results obtained by Srivastava et al [7] and Rjoub and Awwad [15]. Test results of concrete listed in Table 2 showed that the concrete of 10% silica content, increased the compressive strength by about 7 percent. And 15 percent increase of silica content improved the compressive strength by about 32.7 percent.

Table 2. Effect of silica content on the compressive strength of the PLWAC

Concrete compressive strength, MPa	Silica content %			
	0%	10%	15%	20%
Cubic strength*, f_{cu}	14.7	15.7	19.5	17.7
Cylindrical strength**, f'_c	11.76	12.56	15.6	14.16

* Cubic strength: Cubes of 150×150×150mm.

** Cylindrical strength transformed via multiplying f_{cu} by 0.8 to obtain the f'_c of 150×00 mm.

**Figure 5. Effect of silica powder content on the cubic compressive strength of the PLWAC**

3. Results and Discussions

Bond strength is determined by applying direct shear force, P on the concrete-stone interface, as shown in Figure (6-a). Force, P is gradually increased until failure. Failure occurs by one of the following modes. The first is the bond mode, and the second is the shear in the concrete core. The bond mode that occurred by stripping building stones from the backing concrete occurred in the no- or shallow groove depth specimens.

And the specimens of the high bond between concrete and building stones failed by shearing the concrete core, which is the case of the deep groove specimens. The bond strength expressed by the shear stress, τ_{test} is found for the tested specimens by the following equation.

$$\tau_{\text{test}} = \frac{P}{2 A_0} \quad (1)$$

Where: P is the maximum failure load and A_0 equals $b \times h$, where b and h are respectively the width and height of test specimens as shown in Figure (4-a).

The test shear value, τ_{test} represents the bond strength required to strip the stone from its backing concrete (Figure 6b). On the other hand, the shear strengths of specimens failed by shearing the concrete core form an upper limit of the bond strength as well as the concrete shear strength, ν_c , of the core (Figure 6c). So, the bond and shear strengths are calculated according to Equation 1 and listed in Table 3. Each value represents the average of two specimen's test results.



Figure 6. Testing specimens: Applying direct shear to the tested specimens: a) Specimen in testing machine b) Shear in concrete core (shear mode of failure) c) Bond failure mode (Stripping stone).

The increase in the bond strength resulted from silica addition is obtained and listed in Table 3. The tabulated results show that the average increase in the bond strength is about 14 percent for concrete containing 10% of silica content, while the 15% content increased the bond strength by about 33%. The bond strength is plotted in terms of the silica content for different stone surface roughness and shown in Figure 7. The plot shows that the bond force increases as the silica content increases with an optimum content of about 15%.

Similarly, the bonding stresses are plotted against the relative roughness of the stone surface, A_m as shown in Figure 8. The figure shows that the bond increases as the relative roughness of the stone surface increases up to an upper limit encountered in specimens failed by shear in the concrete core.

Table 3. Effect of silica content on the bond strength, τ_{test} [MPa]

Silica content	0% τ_0	10% τ_{10}	Increase % $(\tau_{10} - \tau_0)/\tau_0$	15% τ_{15}	Increase % $(\tau_{15} - \tau_0)/\tau_0$	20% τ_{20}
$A_m = 1.0$	0.42	0.52	23.8%	0.62	47.6	0.41
$A_m = 1.12$	0.5	0.63	26 %	0.7	40	0.47
$A_m = 1.24$	0.61	0.6	-1.6 %	0.73	19.8	0.54
$A_m = 1.48$	0.65	0.7	7.7 %	0.82	26.1	0.57
$A_m = 1.95^v$	0.65 ^v	0.67 ^v	-	0.79 ^v	-	0.67 ^v
Average of increase in bond strength			14 %	33.4 %		

Notes: A: is the roughened concrete-stone interface area.

A_0 is the surface area of no groove specimens = 145×125 mm

A_m is the relative roughness of stone surface $A_m = A/A_0$.

^v failure controlled by shearing concrete core (deep groove specimens).

τ_0 , τ_{10} , τ_{15} and τ_{20} are bond strengths of concrete containing 0, 10, 15 and 20% of silica, respectively

The plot shows that the maximum bond corresponds to about 50% increase in the stone roughness, where the relative roughness, A_m , is about 1.5. The upper curve also shows that the maximum bond corresponds to mixes of silica contents of about 15% of cement weight.

3.1. Predicting Bond Strength

The bond strength is affected by some parameters such as the unit weight of concrete, w_c , the concrete compressive strength, f'_c , the silica content, and the relative surface roughness of the stones, A_m . As the concrete strength increases the silica percentage increases with 15% upper limit; it is then assumed that the concrete strength covers the concrete content. Therefore, the predicted bond strength, τ_p , is written in the following form:

$$\tau_p = X_b \lambda A_m \sqrt{f'_c} \quad (2)$$

Where: λ is the modification coefficient, which accounts for the concrete density, w_c .

A_m is the relative roughness of the stone surface, $A_m = A/A_0$.

f'_c is the concrete compressive strength, MPa.

X_b is a bond coefficient obtained from test results corresponding to the bond failure mode.

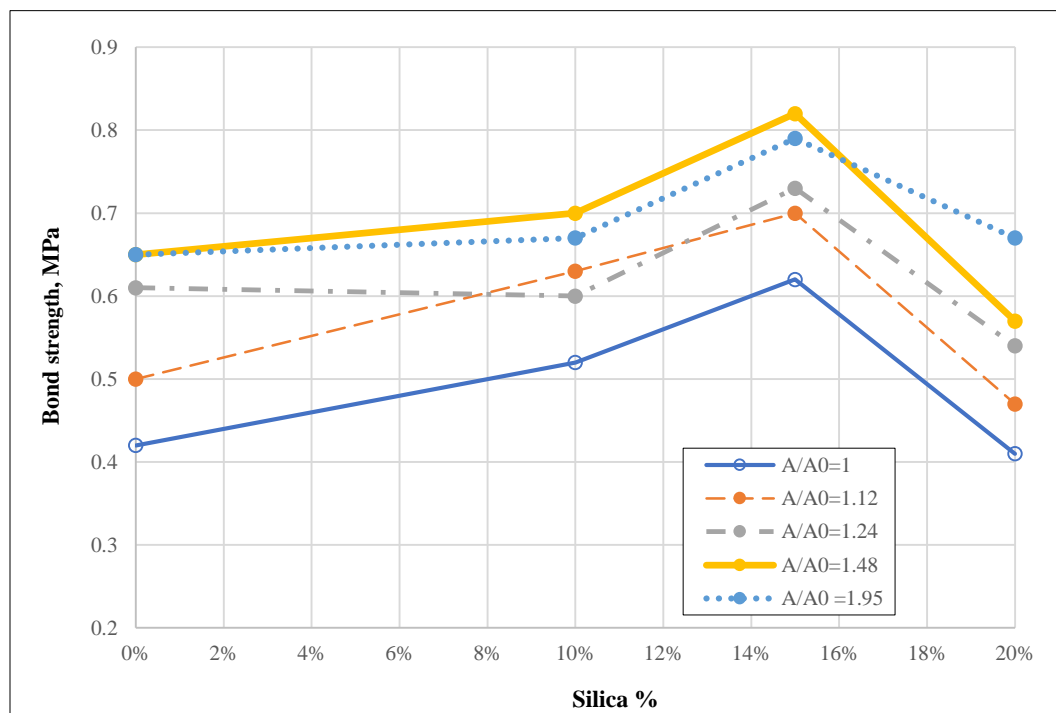


Figure 7. Bond strength vs. silica powder content for different stone concrete roughness

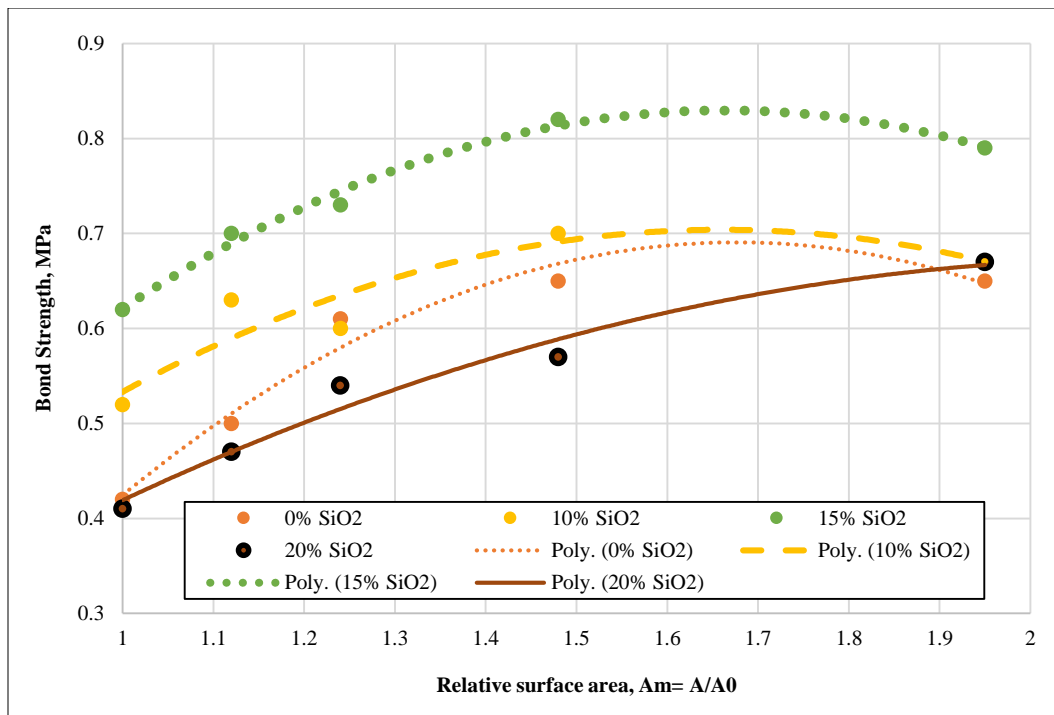


Figure 8. Bond strength (τ_{test}) vs. stone roughness (A_m) for different silica powder contents

3.1.1. Concrete Unit Weight, w_c

The ACI 318-19 [17] adopted a method of determining the modification factor, λ , used for reducing the mechanical properties of lightweight concrete compared with normal-weight concrete. The Code uses the value of the factor λ in the design of lightweight concrete for shear strength, friction properties, splitting resistance, bond between concrete and reinforcing steel, and development length requirements.

In the ACI318-19 [17], the factor λ is expressed in terms of the concrete density, w_c where the factor λ equals $(0.000469 w_c)$ when w_c is between 1600 and 2160 kg/m³. With a lower limit of 0.75 when w_c is less than 1600 kg/m³, and an upper limit equals 1.0 when w_c is more than 2160 kg/m³. In this research work, the factor λ equals 0.75 where the density of concrete was 1402 kg/m³.

3.1.2. Obtaining the Value of the Coefficient, X_b

The value of the coefficient X_b is assumed to represent the average value of $[\tau_{test} / (A_m \lambda \sqrt{f'_c})]$ for all specimens that failed in bond mode of failure. The average was 0.189 and Equation 2 that predicts the bond strength, τ_p has the following form.

$$\tau_p = 0.189 \lambda A_m \sqrt{f'_c} \quad (3)$$

3.2. Concrete Shear Strength

Similarly, as the deep groove specimens failed by shearing the concrete core, the values of the term, τ_{test} represent the shear strength of the concrete, v_c , that is assumed to have the form $[v_c = X_v \lambda \sqrt{f'_c}]$. The value of the coefficient, X_v is found as the average value of the term $[v_c / (\lambda \sqrt{f'_c})]$ for specimens failed by shear in the concrete core (Listed in Table 4). The obtained value of X_v is 0.26, and consequently, the concrete shear strength of the core, v_c , is given by the following expression.

$$v_c = 0.26 \lambda \sqrt{f'_c} \quad (4)$$

It is worth mentioning that the obtained value of X_v lies on the lower bound of the results obtained by Helmick et al. [18], where they found that the value of X_v in the direct shear tests ranges from 0.29 and 0.62.

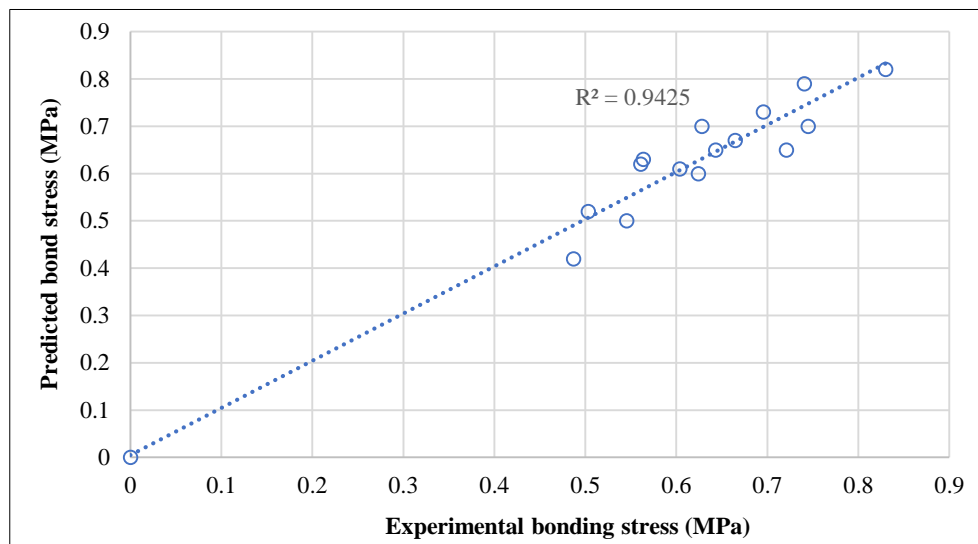
3.3. Test Versus Predicted Bond Strength

Comparison between experimental bond strengths and the corresponding predicted values obtained by Equations 3 and 4 are listed in Table 5 and plotted in Figure 9. Results of the test and predictions show good agreement.

Table 5. Predicted bond and shear strengths, τ_p and v_c compared with the experimental test values

Roughness, A_m	Relative surface									
	$A_m = 1$		$A_m = 1.12$		$A_m = 1.24$		$A_m = 1.48$		$A_m = 1.95$	
Silica content % of cement	τ_{test} [MPa]	$\tau_{predicted}$ [MPa]	τ_{test} [MPa]	$\tau_{predicted}$ [MPa]	τ_{test} [MPa]	$\tau_{predicted}$ [MPa]	τ_{test} [MPa]	$\tau_{predicted}$ [MPa]	$v_{c, test}$ [MPa]	$v_{c, predicted}$ [MPa]
0 %	0.42	0.48	0.5	0.55	0.61	0.6	0.65	0.67*	0.65*	0.67*
10 %	0.52	0.50	0.63	0.56	0.6	0.62	0.7	0.69*	0.67*	0.69*
15 %	0.62	0.56	0.7	0.63	0.73	0.7	0.82*	0.77*	0.79*	0.77*

* Failure controlled by shearing the concrete core and (τ_{test} represents concrete shear strength, v_c).

**Figure 9. Predicted versus experimental bonding strength**

4. Conclusions and Recommendations

This study investigated the bond between PLWAC and the building stones. The influence of partial replacement of cement by silica powder to the concrete mix on the bond and compressive strengths is studied, and the following conclusions drawn from this research work:

- A relation that predicts bond and shear strengths of pumice lightweight aggregate concrete PLWAC is proposed;
- The addition of silica powder to the PLWAC increases the concrete compressive strength, the bond strength, as well as the concrete shear strength with the upper limit;
- The upper limit corresponding to the optimum silica content is about 15 percent, where the strength starts to decline when specimens contained higher silica contents;
- The increase in compression strength was 7 percent for concrete containing 10% silica compared with the no silica concrete. And the increase reached about 32% for concrete for 15% for silica;
- Increase in the bond strength, was 14 and 33.3% for silica contents of 10 and 15%, respectively;
- All saw-cut specimens failed by stone stripping in a bond mode of failure;
- The bonding stress increases as the relative roughness of the stone surface increases with an optimum value of about 150%;
- When the relative roughness of the stone surface exceeds 150%, the failure is controlled by shearing the concrete core instead of stripping the building stones.

The author recommends extending studying the bond of concretes of higher strengths and using different types of building stones such as basalt or other types of hard stones.

5. Declarations

5.1. Data Availability Statement

The data presented in this study are available in article.

5.2. Funding

The funding of this paper is supported by LAFARGE- Jordan and Al-Balqa' Applied University. The materials were supplied by LAFARGE-Jordan, and the experimental tests were conducted at the Civil Engineering labs at Al-Balqa Applied University.

5.3. Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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