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The Mechanical Properties of Portland Cement Reinforced by Short and Long Particles Made from Different Metals

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Abstract This work investigates the effects of adding different types of metals (aluminum, galvanized steel and copper) of short (2 mm length) and long (5 mm length) particles to the cement matrix phase. The aim was to increase the compressive mechanical properties of the concrete by strengthening it with different types and lengths of certain metals. The new metal particles can be successfully combined into the cement paste. It was found that the short and long particles of aluminium have negative effects on the compressive mechanical properties. The failure stress of these reinforced materials decreased as compared to the unreinforced cement. However, there were some increases in failure stress in the steel-cement composite specimens due to the reinforcement using steel short and long-particles. The average failure stresses reached 15 and 19 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively), as compared to that of unreinforced cement. Moreover, there were noticeably large increase in failure stress in the metal-cement composite specimens was achieved due to the reinforcement of short and long-particles of cupper. The average failure stresses were increased to 12.6 and 26.6 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively). These values are higher than that of unreinforced cement with an average failure stress of 10.6 MPa. Finally, it was concluded that the addition of different types and length of metal can increase the specific strength (σ/ρ) of cement, with the highest increase obtained by the reinforcement condition where long (5 mm) cupper particles are used. The average value reached 8.2 MPa g^{-1} cm^{-3} as compared to an average value of 5 MPa g^{-1} cm^{-3} for the unreinforced cement specimens.
Keywords: Portland cement, Reinforcement, Metal Particles, Compressive and Specific Strength.

الخواص الميكانيكية للأسمنت البورتلاندي المقوى بالجسيمات القصيرة والطويلة المصنوعة من معادن مختلفة

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الملخص يهدف هذا البحث إلى دراسة تأثيرات إضافة أنواع مختلفة من المعادن (الألمنيوم والنحاس والصلب المجلفن) بطول قصير (2 مم) وطويل (5 مم) إلى خلطة الأسمنت. والهدف من ذلك هو زيادة الخواص الميكانيكية للخرسانة من خلال تعزيزها بأنواع وأطوال مختلفة من معادن معينة. ويمكن الجمع بين الجسيمات المعدنية الجديدة بنجاح في معجون الاسمنت. وقد وجد أن الجسيمات القصيرة والطويلة من الألمنيوم لها آثار سلبية على الخواص الميكانيكية اثناء اختبار الضغط. حيث انخفض الإجهاد الناجم عن هذه المواد المقواة بالمقارنة مع الأسمنت غير المقوى. أضافة الى ذلك،هناك بعض الزيادات في اجهاد الفشل في عينات الصلب والاسمنت المركب بسبب التعزيز باستخدام جزيئات حديد الصلب القصيرة والطويلة. حيث بلغ متوسط شدة الفشل 15 و19 ميجا باسكال (بالنسبة للجسيمات القصيرة 2 مم والطويلة 5 ملم على التوالي)، بالمقارنة مع الأسمنت غير المقوى. علاوة على ذلك، فقد تحققت زيادة كبيرة بشكل ملحوظ في اجهاد الفشل في العينات المركبة من الأسمنت والمعادن بسبب تعزيز الجسيمات القصيرة والطويلة من معدن النحاس. تم زيادة متوسط قوة اجهاد الفشل إلى 12.6 و26.6 ميجا باسكال (للجسيمات القصيرة 2 مم والطولية 5 ملم على التوالي). هذه القيم هي أعلى مقارنة بالأسمنت غير المسلححيث متوسط الإجهاد فشل 10.6 ميجا باسكال. كذلك، تم التوصل إلى أن إضافة أنواع واطوال مختلفة من المعادن يمكن أن تزيد من القوة المحددة (σ / ρ) من الاسمنت، مع أعلى زيادة تم الحصول عليها من حالة التعزيز حيث تم استخدام جسيمات طويلة (5 مم) من معدن النحاس. بلغ متوسط القيمة 8.2 ميجا باسكال /غرام/سم3 مقارنة بمتوسط 5 ميجا باسكال /غرام/سم3 لعينات الأسمنت غير المقوى. وأخيرا، يلقي هذا العمل بعض الضوء على التحسينات المحتملة في الخواص الميكانيكية للأسمنت التي يتم تعزيزها بالأسلاك النحاسية. ويمكن استخدام هذه الخرسانة / المركباتا لقوية في المباني التي تتطلب سلامة وحماية كبيرة مثل البنوك والمخازن العسكرية والمستودعات والسلع التموينية وغيرها.

الكلمات الرئيسية: أسمنت بورتلاندي، التعزيز، الجسيمات المعدنية، قوة الضغط والقوة المحددة للعينات.

1.Introduction: Concrete is a composite material that is extensively used in buildings and construction field. It is used in various applications such as buildings, bridges, highway pavements, sidewalks, home construction, dams, etc. [1-2]. Basic concrete mix components consist of cement, aggregates (sand and gravel), and water, and in some other cases it is possible to include other components to the mixture to improve the physical and mechanical properties of the concrete [3]. To achieve a strong, workable and durable concrete, the mix proportions between the various components must be carefully controlled. Less cement paste can lead to more voids, which produce less strength and durability while more cement paste can lead to more shrinkage and less durability. The gradation and the ratio of fine aggregates to coarse aggregates can affect strength and porosity. The mix design should also achieve the desired workability of concrete so as to prevent segregation and allow for ease of placement. Typically, a concrete mix is about 7 % to 15% cement, 24 % to 30% sand, 31% to 50% percent aggregate and 14% to 20% water [3]. Entrained air (5% to 7%) is also added to concrete to improve durability [1-4]. Concrete should have enough compressive strength and flexural strength to support applied loads. At the same time, it should have good durability to increase its design life and reduce maintenance costs.Several studies have reported improvements in mechanical and durability properties after reinforcing cement with, for instance, up to 60 % of fine glass powder [5-6], and also with up to 10 % of mineral additives (natural zeolite and aluminosilicate) [7-8]. Moreover, Alizadeh et al. [9] studied the effect of using electric arc furnace steel slag on reinforcement of concrete. Experimental results showed that the steel slag aggregate concrete provide higher compressive properties, (e.g. tensile and flexural strength and modulus of elasticity), compared to natural aggregate concrete. Ali N. Alzaed [10] investigated the effect of iron filing in concrete compressive and tensile strengths. Generally, it was found that concrete compressive strength increased gradually when iron filing added to the concrete mix (0, 10, 20 and 30 %). The compressive strength increased by 17% when 30% of iron filling added to the concrete mix. However, tensile strength increased by 13% when 10% of iron filling added to concrete mix. There is a small effect on tensile strength with increasing the iron content. Recent work (S. Ghannam et al. [11]) reported different trends of results, in which granite powder and iron powder were used as a partial replacement of sand in concrete. For mixes with iron powder the compressive, flexural, and tensile strength increased gradually with the increase in the iron powder ratio (5, 10, 15 and 20 %). The strength increased from 35.8 MPa for unreinforced concrete to 47.7 MPa for 20 % iron-reinforced concrete. This is about 33 % increase in compressive strength. Nevertheless, there are very limited studies that explore the use of metal fibers or particles as reinforcement for cement materials. One example is the study that examined the properties of a new fiber cement material made by incorporating short ductile copper fibers randomly distributed in Portland cement paste and compacted by compression to 35 MPa [12]. The compacted copper fiber cement composite had optimum properties with fibre fraction of 4%, fibre, diameter = 0.16 mm and fiber length of 18 mm. The inclusion of the copper fibers at optimum reinforcement produced strength increases of up to 50% in the moist state and of up to 20% in the dry state (e.g. strength increased from 18.3 to 22.7 MPa).Other work [13] investigated the behavior of cement/polystyrene composite with improved strength and ductility. The data reported for the Young's modulus and compressive strength of composite cement foams indicated that the sandwich effect begins at volume fractions of spheres of 20%-30%. The maximum effect occurs at volume fractions of spheres of 45%-50%. Such cement foam composites have a number of properties, which make them attractive for use in the cores of building panels: low cost, adequate mechanical properties, adequate thermal insulation, and good fire resistance.

2. Experimental Procedures:

In this experiment, the effects of adding some metals in various sizes and shapes to the cement were studied, for the purpose of improving the mechanical properties of concrete.

2.1. Materials Used

Different types of materials were used. These are cement, water, aluminium, steel and copper particles. Details on each type of these materials are now discussed.

2.1.1. Cement

The city of Zliten has the largest manufacturers of cement production in Libya. The Cement used in this work is Portland cement made in Zliten, which is readily available from the local market.

2.1.2. Water

Potable water from Sebha city was used for the experimentation as a part of the ingredients. The chemical composition of the same water has been recorded in ref. [14]. The amount of water was measured using the injection needle (ml). The amount of water in every sample was 100 millilitre.

2.1.3. The Mold

A plastic mold was used in this work for casting the concrete paste. It is the part of medical injection needle as shown in figure 2.1 below.

Figure 2.1 – The plastic mold used for casting cement specimens

2.1.4. Aluminum, Galvanized Steel and Cupper Particles:

Different types of metal particles were used in this work. The particles were obtained from cutting metal wires purchased from the Libyan local market to certain sizes. The chemical compositions of these different metal wires can be found in different information sources which are available to the public, e.g. in ref. [15 – 16]. The aluminum wires are used in electrical wiring in modern building construction and welding applications. The galvanized steel, also known as tie wire, is an annealed wire suitable for tying bars and mesh in reinforcing concrete. The copper wires are the ones used for electrical and electronic applications. The short particles have a length of 2 mm, whereas the long particles have length of 5 mm, as shown in figure (2.2).

Figure 2.2 - Different types of metal particles used in this work The particles were classified into two types in size (2mm and 5mm) particles as shown in the figure (2.3) below.

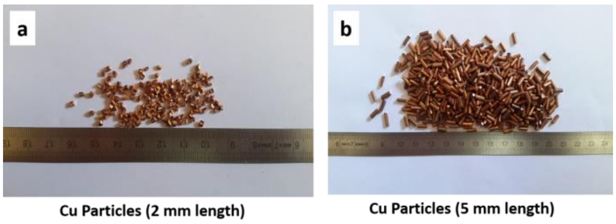


Figure (2.3) - Example of cupper particles classified into two types in length of a) 2 mm and b) 5 mm.

The diameter of particles were also measured and found to be 2 mm, as shown in the figure below.

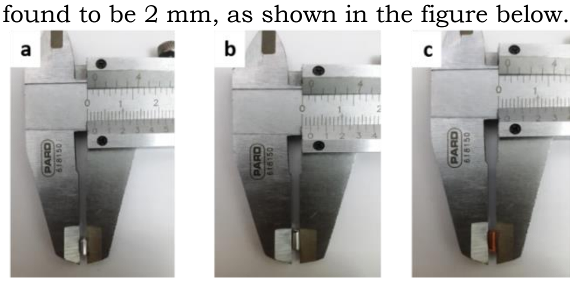


Figure 2.4 - The measurement of the diameter of the different particles a) aluminum b) galvanized steel, c) cupper.

2.2. Mixing Specification

The mixture of the proposed cement-metal composite was carried out using consistent method for all reinforcement conditions. Short and long-particles of different metals were added to the cement by specific weight. 40g of metal particles is added to 60g of cement, with addition of 100 ml of water. This represents about 40 % of metal particles that is mixed with cement and water, as specified in previous work [1-4, 13]. The short and long metal particles were added to the cement by sprinkling on the cement liquid to maintain equal particle distribution while mixing together, as shown in figure 2.5 below.

Figure 2.5 - Copper particles (each with diameter of 2 mm) distributed in the cement paste.

To ensure accurate processing of specimens and so accurate results, the weight of the different metal particles were measured using a sensitive electronic balance, as shown in the figure (2.6) below.

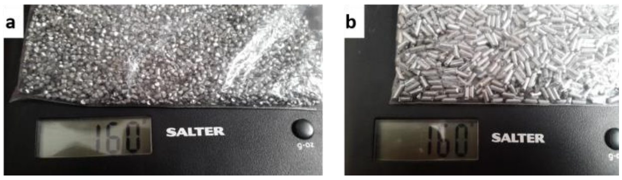
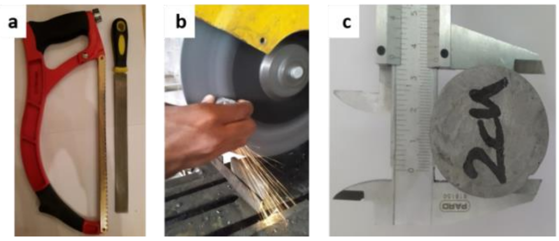


Figure 2.6 –Examples of measuring the weight of the aluminum particles with a) 2 mm length and b) 5 mm length.

2.3. Cutting of Samples

All as-cast metal particle-cement samples were cut down into specimens of a specific size. The new specimens were 35 mm in diameter and 30 mm in length. The handsaw and sand paper was used for cutting the samples, top and the bottom surfaces were grounded and levelled using electrical saw, as shown in figures (2.7) below.



Type of Reinforcement	L. of Wires	Spe. No.	Failure σ (MPa)	Av. σ (MPa)	Mass (g)	Specific. σ (MPa g^{-1} cm^{-1})
None	None	1	11.7	10.6	56	5.4
		2	9.5		54	4.5
		3	10.6		55	5
(Al)	2 mm	1	7	4.7	59	3.1
		2	5.6		60	2.4
		3	1.4		54	0.7
	5 mm	1	6.8	6	60	3
		2	5.8		56	2.7
		3	6		51	3
(Fe)	2 mm	1	29.8	17	79	9.8
		2	9.3		78	3.1
		3	12.1		77	4.1
	5 mm	1	36	19	80	11.9
		2	13		75	4.4
		3	9		74	2.5
(Cu)	2 mm	1	22.8	14	80	7.4
		2	9.2		87	2.8
		3	9.6		89	2.8
	5 mm	1	21	26.6	85	6.4
		2	39		89	11.4
		3	20		75	6.9

Figure 2.7 – The process of cutting and preparing the specimens using a) manual cutting tools, b) electrical saw and c) final surface finish.

After all processes of cutting and surface finish were completed, measuring the total length, diameter and weight of every specimen were carried out to be ready for compression test as shown in the figure (2.8) below.

Figure 2.8 –The types of samples following the process of cutting, surface finish and weight measurement

2.4. Compression Tests

In this work, 21 specimens were tested mechanically; this includes three samples for every condition. The specimens were compressed using ELE international machine model with load speed of 0.92 N/s. From the data produced, the values of the failure stress (MPa) for each specimen is extracted. The specific strength (strength divided by the density of the sample) are also calculated. As shown in the figure (2.9) below.

Figure 2.9 – a) and b) ELE international compression machine, c) showing sample after crushing test.

3. Results and Discussions

In this part of the present work, analysis of the data from the experimental work is explained. Data includes failure stress, the average failure stress for each condition and the calculation of the specific strength (σ/ρ) to envisage the exact benefits in cement properties from such reinforcement. Compression tests were performed on all reinforced cement specimens and data is reported in table 3.1.

The failure stress was calculated by first converting all values from KN to N (x 10^3) and then dividing by the cross section area (572.26 mm^2). This gives the values of failure stress in MPa.

Different trends of data can be observed from the mechanical testing results. There are both positive and negative effects from the present method of reinforcement. Figure 3.1 shows the average failure stress for the unreinforced cement specimens and cement reinforced with different metals.

Table 3.1 - Results from compression test for all types of unreinforced and metal-reinforced cement composites. Mechanical properties such as failure load (KN) and failure stress (MPa), specific strength (MPa g^{-1} cm^{-1}) for every specimen are recorded.

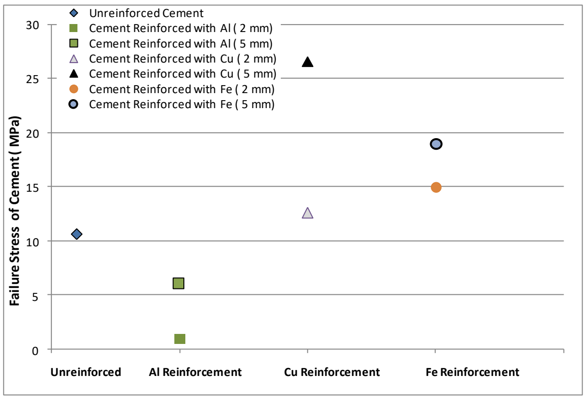


Figure 3.1 - The average failure stress (MPa) for the unreinforced cement specimens and cement reinforced with different metals.

It can be seen that aluminum reinforcement has a negative effects on the mechanical properties of cement. The cement specimens that were reinforced with short and long- aluminum rods failed at lower stresses as compared to the unreinforced specimens. The average failure stresses were recorded as 4.7 and 6.2 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively), which is lower than that of unreinforced cement with an average failure stress of 10.6 MPa. This can be explained by the fact that aluminum has lower density (2.7 g/cm^3) [15] than that of cement (3.15 g/cm^3) [1], which means that the aluminum has less load supporting capacity than that of the cement. Since the aluminum occupies certain volume fraction within the specimens (40 % wt.), then it is expected that such low density and low strength metals would bring some weakness to the cement, and this is why these specimens failed at low stresses.

Moreover, different trend of mechanical properties results were recorded for the steel particles reinforcement. There were some increases in failure stress in the iron-cement composite specimens due to the new reinforcement using iron short and long-particles. The average failure stresses were recorded as 17 and 19 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively). These values are higher than that of unreinforced cement with an average failure stress of 10.6 MPa. This can be explained by the fact that steel has much higher density (7.87 g/cm3) [15] than that of cement (3.15 g/cm3), which means that the steel has much higher load supporting capacity than the cement. Since the iron occupies certain volume fraction within the specimens (40 % wt.), then it is expected that such higher density and higher strength metals would bring an increase in strength to the cement, and this is why these specimens failed at higher stresses of 17 and 19 MPa.

Furthermore, there are noticeable increases in failure stress in the metal-cement composite specimens due to the new reinforcement method when using cupper short and long-particles. The average failure stresses were recorded as 14 and 26.6 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively). These values are higher than that of unreinforced cement with an average failure stress of 10.6 MPa. This can be explained by the fact that cupper has much higher density (8.95 g/cm^3) [15] than that of cement (3.15 g/cm^3), which means that the cupper has much higher load supporting capacity than the cement. Since the cupper occupies certain volume fraction within the specimens, then it is expected that such higher density and higher strength metals would bring an increase in strength to the cement, and this is why these specimens failed at higher stresses of 12.6 and 26.6 MPa.

Here it is noticed that the long metal particles (5 mm) have more effects on the cement mechanical properties than the short particles (2 mm) of the same metals. This effect has been explained previously in ref. [16]. It is stated that some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length Lc is dependent on:

The fiber diameter (d)

- Its ultimate (or tensile) strength σ_f
- The fiber–matrix bond strength (or the shear yield strength of the matrix, whichever is smaller) τ_c according to:

$$L_c = \frac{\sigma_f^* d}{2\tau_c} \qquad (3.1)$$

When a stress equal to σ_f^* is applied to a short fiber of lengths significantly less than Lc, the matrix deforms around the fiber such that there is almost no stress transference and little reinforcement by the fiber. However, as the length of the fiber reaches this critical length, the maximum fiber load is achieved only at the axial center of the fiber. As fiber length L increases, the fiber reinforcement becomes more effective. Therefore, to produce a significant improvement in strength of the composite, the fibers must be continuous (long) [16]. In structural engineering design, materials with high strength and low weight would be attractive for many applications. This means that the weight-specific strength is of great interest, which can be calculated by the strength divided by the density (σ/ρ). The exact criteria vary depending on the types and length of metal short-rods condition. The weight-specific strength in this case can be classified as axial specific strength (σ/ρ) [17-18]. It is clearly seen that the addition of different types and length of metal can increase the cement axial specific strength, with the highest increase obtained by the reinforcement condition where long (5 mm) cupper particles are used. The average value reached 8.2MPa g-1cm-3as compared to an average value of 5MPa g^{-1} cm^{-3} for the unreinforced cement specimens. The short 2 mm cupper particles had lower effects on the specific strength of cement, with an average value reaching 4.3 MPa g^{-1} cm^{-3}. Furthermore, the short and long- particles of galvanized steel have more positive effect on the specific strength of cement than that of aluminum. The average specific strength obtained from the cement reinforced by steel recorded values of 5.7 and 6.3 MPa g^{-1} cm^{-3}.

These values are obtained from the 2 and 5 mm iron particles reinforced cement respectively.
Finally, the average specific strength obtained from the cement reinforced by aluminum recorded lower values of 2 and 3 MPa g^{-1} cm^{-3}. These values are obtained from the 2 and 5 mm aluminum particles reinforced cement respectively.

4. Conclusions:

The overall conclusion is that the different metal particles can be successfully incorporated into the cement specimens. The other conclusions can be summarized as follows:

1. It was found that the short and long particles of aluminum have negative effects on the compressive mechanical properties. The failure stress of these reinforced materials decreased as compared to the unreinforced cement.
2. There were some increases in failure stress in the steel-cement composite specimens due to the reinforcement using steel short and long-particles. The average failure stresses reached 17 and 19 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively), as compared to that of unreinforced cement.
3. However, there were relatively large increase in failure stress in the metal-cement composite specimens due to the reinforcement using cupper short and long-particles. The average failure stresses were increased to 14 and 26.6 MPa (for the short 2 mm and long 5 mm particles reinforced cements respectively). These values are higher than that of unreinforced cement with an average failure stress of 10.6 MPa.
4. It is clearly seen that the addition of different types and length of metal can increase the specific strength of cement, with the highest increase obtained by the reinforcement condition where long (5 mm) cupper particles are used. The average value reached 8.2 MPa g-1 cm-3 as compared to an average value of 5 MPa g^{-1} cm^{-3} for the unreinforced cement specimens.
5. Finally, this work sheds some light on the potential improvement in mechanical properties of cement that is reinforced with copper wires. Such strong concrete/composites can be used in buildings that require significant safety and protection such as banks, military stores, warehouses, supply commodities etc.

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