ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

STRENGTH AND ABRASION RESISTANCE OF RECYCLED LEAD SLAG MORTAR AT HIGH TEMPERATURES

M. H. Seleem

Materials Engineering Department, Zagazig University, Zagazig, Egypt.

ABSTRACT

The effect of high temperatures on the compressive strength and abrasion resistance of mortar fabricated by using lead slag extracted from recycling of the spent batteries in the homely workshops as fine aggregates was experimentally investigated. The fine lead slag (FLS) was used as a partial replacement of the total fine aggregate (TFA), sand, by different percentages of volume (FLS/TFA = 0, 10, 20, 30 and 40%). Test specimens were subjected to high temperatures ranging from 200°C to 700°C step 100°C. The exposure time after reaching the desired target temperature kept at two hours. The sequence of the residual unstressed test was followed. The weight loss and the relative compressive strength (strength of heated specimen to that of the corresponding unheated specimen) were determined. The weight loss of the heated and unheated specimens due to exposure to abrasive wear was also calculated. Test results indicated that, at certain FLS/TFA%, the relative compressive strength decreased gradually with high temperature up to 500°C and after that it showed a sudden drop with further increases in temperature. The abrasion resistance decreased with increasing high temperature. The compressive strength and abrasion resistance of mortar increased up to replacement of 20% of sand by FLS and after that it decreased but still higher than that of 100% sand. Both compressive strength and abrasion resistance of FLS mortar relative to those of 100% sand enhanced clearly with the presence of FLS at temperature above 500°C.

يتناول هذا بالبحث بالدراسة المعملية تأثير درجات الحرارة العالية على مونة الخرسانة الأسمنتية والمصنوعة من خبث الرصاص المستخرج من اعادة تدوير البطاريات المستهلكة فى الورش الأهلية كاحلال جزئى للرمل بنسب صفر، ١٠%، ٢٠%، ٣٠%، ٤٠%. وتم تعريض عينات المونة لدرجات حرارة مختلفة (درجة حرارة الغرفة، ٢٠٠، ٣٠٠، ٤٠٠، ٥٠٠، ٦٠٠ ، ٧٠٠ م°) وذلك لزمن قدره ساعتان. وتم اختبار العينات بعد تسخينها فى الفرن للزمن المطلوب وتبريدها فى الهواء عند درجة حرارة الغرفة. وتم التقييم على اساس مقاومة الضغط المنسوبة الى مقاومة الضغط للعينات المناظرة والتى لم يتم تعريضها للحرارة وكذلك مقاومة البرى والفقد فى الوزن نتيجة التعرض لدرجة الحرارة. وقد أوضحت النتائج أن مقاومة الضغط وكذلك مقاومة البرى تقل مع زيادة درجة الحرارة وأن أحسن نسبة لاحلال الرمل بالخبث هى ٢٠%. كما أوضحت النتائج أن مقاومة الضغط النسبية وكذلك مقاومة البرى النسبية (منسوبة الى العينات التى تحتوى على نسبة ١٠٠% رمل) تكون عالية عند درجات الحرارة أعلى من ٥٠٠م°.

Keywords: Recycled lead-slag; Mortar; High temperature; Compressive strength; Abrasion resistance.

1. INTRODUCTION

The high consumption of natural sources, the high amount of industrial wastes and environmental pollution require new solutions for a sustainable development. One of the major contributions to the preservation of the environment and sustainable development is the reuse and recycling of the waste materials. Use of inorganic industrial residual products in making cementations products as concrete and mortar will lead to sustainable concrete design and a greener environment [1].

The need to develop concrete and mortar with non-conventional aggregates is urgent for environmental as well as economic reasons. A review of earlier research showed that industrial as well as other wastes have been used in concrete-making to improve the properties of concrete and to reduce cost. Inclusion of recycled tire rubber fibers in concrete was found to avoid the opening of cracks and increase energy absorption [2]. Structural light weight concrete has been produced using oil palm shells [3] and demolished masonry waste [4] as aggregates. An improvement in the modulus of elasticity of concrete was observed with partial replacement of crushed stone coarse aggregate by crushed vitrified soil aggregate [5].

Compressive strength and abrasion resistance were increased when crushed ceramic waste was used to partially replace conventional gravel coarse aggregate [6]. On the other hand, De Brito et al [7] found that strength decreases as the quantity of ceramic aggregates in concrete increases and the decrease in compressive strength is higher than that in the flexural strength. While, the abrasion resistance of concrete made with ceramic recycled aggregates is higher than that of concrete made with limestone aggregates. Durability of cementatious materials like mortar and concrete is as important as compressive strength.

In recent published work by the author and co-workers [8], lead slag extracted from recycling of the spent batteries in the homely workshops was used as concrete aggregate. Short term mechanical properties, wear resistance and radiation absorption were studied. In the same year, Penpolcharoen [9] published the second contribution in the use of secondary lead slag as a construction material. He found that all samples exhibited higher compressive strengths than that of the sample without slag, which increased with increasing the slag contents and ages. The highest compressive strength was found for the sample containing 20% slag as cement replacement and 100% slag as aggregate replacement.

The results of chemical analysis of the used lead slag in the previous work [8,9] revealed that the oxide components of the slag were similar to those of ordinary Portland cement (OPC). For environmental concern, leachability of lead (Pb) from all samples was also carried out [9] on samples with high slag content. The amounts detected were much lower than the acceptable limit (5 ppm) for the requirement of Thai hazardous waste disposal standard. So, the application of the slag for construction material is fully attractive. The environmental conditions such as temperature, humidity and the mechanism of chemical transports are the major factors causing chemical and physical attacks [10]. Thus, the performance of construction materials fabricated from slag under these conditions is of primary important. So, in the present work, the effect of high temperature on the compressive strength and abrasion resistance of mortar made with lead slag as partial replacement of sand was studied.

2. EXPERIMENTAL WORK

All materials used in this study were locally available materials. The cement used was type I ordinary Portland cement. The sand was siliceous sand with 100% passing ASTM sieve No. 4. The fine lead-slag (FLS) used in this research was obtained by recycling of the spent batteries electrodes in homely workshops. Recycled- lead slag (RLS) was used as fine aggregate in mortar manufacture. The RLS was crushed to the desired gradation by using a roller mill. An energy dispersive X-ray spectroscope was performed to analyze the chemical compositions of the materials. The results of chemical analysis of the used FLS and OPC are given in Table 1. The physical and mechanical properties of the used fine aggregate (sand and FLS) are given in Table 2. Mixing water was clean tap water free from impurities and organic matters. The sand: cement ratio was 3:1 by weight and the water cement ratio was 0.5. The total fine aggregates (TFA) in the mix were partially replaced by FLS particles. The percentages by volume of FLS/TFA were 0, 10%, 20%, 30%, and 40%.

Table 1 Chemical composition of FLS and OPC

Constituent	FLS(wt%)	OPC(wt%)
CaO	2.5	62
SiO_2	12.98	20.39
Al_2O_3	-	5.05
Iron oxide	72.8 as Fe_3O_4	2.89 as Fe_2O_3
MgO	0.26	2.07
K_2O	0.21	0.5
Na_2O	0.53	0.07
SO_3	-	2.4
MnO	0.46	-
Pb	4.1	-
Others	2.33	1.53
L.O.I	3.83	3.1

Table 2 Physical properties of sand and FLS

Property	Sand	FLS
Specific gravity	2.45	4.28
Density, kg/m^3		
Loose	1610	2280
Dense	1700	2820
% Voids		
Loose	38%	47%
Dense	27%	34%
% Water absorption	0.42	3.95
FM	2.55	3.35

Batch materials required for casting twenty one cubes (70 mm side length) for compression test and twenty one cylinders (25 mm diameter and 25 mm height) for abrasive wear test were weighted first. Dry materials for this batch were mixed in the dry state for a time to insure the homogeneity of the mixture before adding the mixing water. The test specimens were removed from the moulds 24 hours after casting and immediately submersed in the curing water for 28 days. A total number of 105 compression specimens and 105 abrasion specimens representing five mixes having different FLS/TFA% were tested.

The experimental program suggested for the present work included the exposure of the mortar specimens to different target temperatures (TT) ranging from 200°C to 700°C step 100°C at an average heating rate of about 10 °C/min. An electric furnace of 1600°C maximum temperature was used. The specimens were placed inside the furnace and the temperature was raised until it reaches the desired target temperature. The specimens were sustained at this target temperature for 2 hours. After that they allowed to cool outside the furnace at room temperature (residual unstressed test sequence), Fig. 1. All cubes specimens were weighted before and after heating to calculate the mass loss due to heating.

A universal-testing machine of 1000 kN maximum capacity was used for the compression test. Among test methods suggested by ASTM for the estimation of the wear resistance of cementitious materials, the revolving disk (ASTM C779, Procedure A) test method [11] was selected. An aggregate abrasion testing machine (Cat. No. EL 42-500) was used to perform the test. The test specimens were exposed to abrasive standard sand, passed from 0.6 mm sieve and retained on 0.45 mm sieve, for 500 revolutions under a load of 750 gm. Each specimen was weighted before and after the test and the weight loss was calculated.

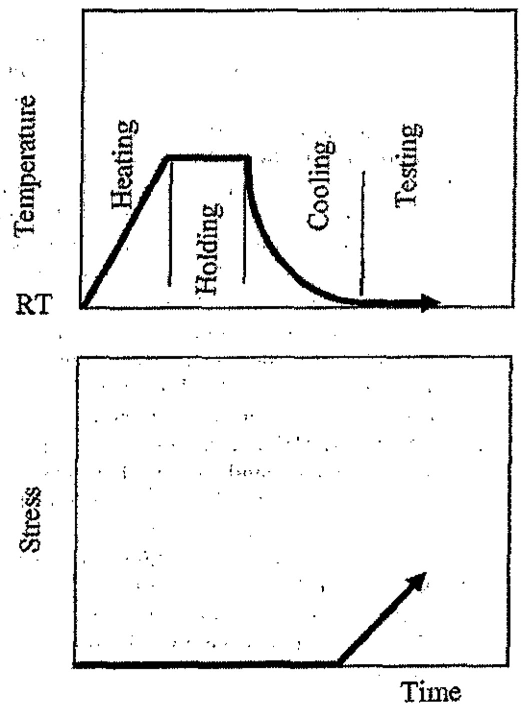


Fig. 1 *Sequence of residual unstressed test followed in this work*

3. RESULTS AND DISCUSSIONS

Density

The effect of FLS/TFA % on the relative density of mortar is illustrated in Fig. 2. The relative density is the ratio of the density of mortar specimen with sand replaced by FLS to that of 100 % sand specimen. The addition of FLS to mortar results in a linear increase in the density of the material to reach 20 % higher than that of 100 % sand at FLS/TFA % equal to 40%.

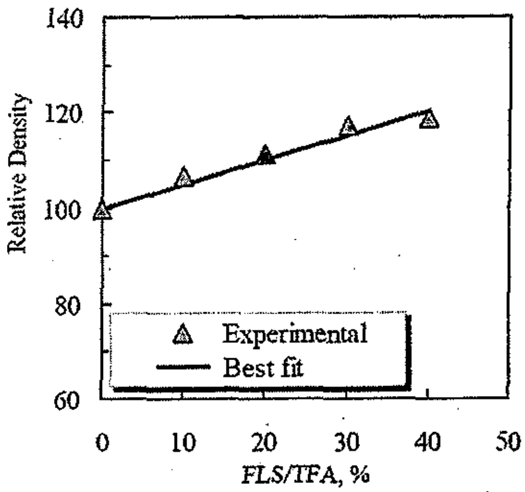


Fig. 2 Effect of FLS/TFA % on the hardened density of concrete mortar.

Mass Loss

The mass losses for the different mortar specimens due to water evaporation as a result of exposure to high temperatures are shown in Fig. 3 for the different FLS/TFA %. The relative mass losses were estimated as the difference in the mass between the unheated and heated specimens to that of the unheated specimens. An increase in the relative mass loss was observed for all mixtures with increasing temperature. The loss rate is high at low temperatures up to 300°C, after that it stabilized before increasing again above 500°C. Similar behavior was observed for concrete specimens but the stabilized stage was ranged between 200°C and 400°C [12]. It is also clear that the mix of FLS/TFA equal to 10 % showed the highest relative mass loss, while that of 40 % FLS recorded the lowest relative mass loss. The mass loss at low temperatures, below 300°C, is caused by quick evaporation of capillary water. Over 400°C, the mass loss is caused by evaporation of chemically combined water (dehydration) and decomposition [13]. Above temperature of 500°C, the dehydration of the chemically combined water of the hydrated Calcium Silicate Hydrate (CSH) resulting in un-hydrated products was accompanied by observable mass loss.

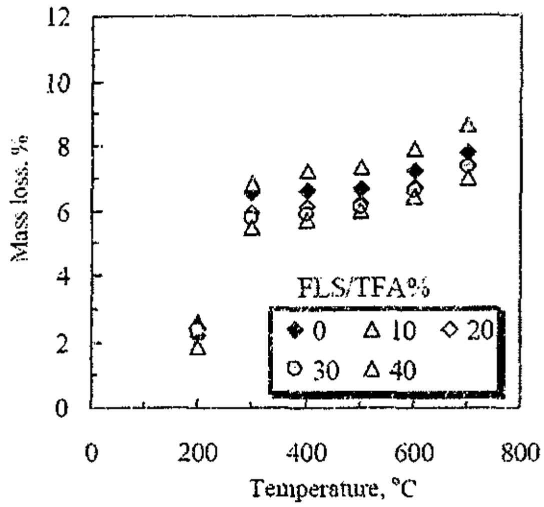


Fig. 3 Effect of high temperature on the mass loss for different FLS/TFA %.

Compressive Strength

The effect of high temperature on the relative compressive strength of mortar specimens with FLS/TFA equal to 0 %, 10%, 20%, 30% and 40 % is shown in Fig. 4. The relative compressive strength here is defined as follows:

Relative compressive strength = $[\sigma_{cHT}/\sigma_{cRT}]\times 100$

Where σ_{cHT} is the compressive strength of the specimen exposed to the desired target temperature and σ_{cRT} is the corresponding compressive strength of the unheated specimens at the same FLS/TFA%. The general trend for the different FLS/TFA % is similar, i.e. with increasing the target temperature, a steady state drop in the relative strength is observed up to a temperature of 500°C, where the average relative strength is about 83%. After 500°C, the average relative strength dropped suddenly to reach 51% with increasing temperature to 600°C. At 700°C, the relative strength reached an average of 36 %. At temperature of 200°C, the average relative strength is 96 %. In a previous work by the author and co-workers [12] on the effect of high temperature on the relative strength of concrete, a sudden drop was recorded in the strength after 200°C and gravel concrete completely lost its strength at 600°C. The absence of coarse aggregate in the mortar decreased the effect of differential thermal expansion that occurred between cement paste and aggregate. This can explain the slow gradual decrease in the relative strength at temperature up to 500°C. The high relative strength at 200°C is attributed to the enforced hydration process due to water evaporation [14]. The structure of the cement mortar after high temperature exposure gets loose because of the pore expansion owing to the vaporization of the absorbed water. The loss of water from the free calcium hydroxide (CH) (results from cement hydration), leaving calcium oxide (quick lime). This calcium oxide absorbs water from the surrounded atmosphere as the specimen leaved cool. Thus it re-hydrated to CH or reacts with atmospheric CO_2 resulting in calcium carbonate ($CaCO_3$). Theses processes are accompanied by an expansion in the volume, which may disrupt the material [13, 15].

To explain the role of FLS/TFA % on controlling the behavior of mortar at high temperature, the compressive strength of the heated mortar specimen with different FLS/TFA% (σ_c) was divided to that with FLS/TFA% equal to 0 (σ_{co}) at the different regimes of high temperatures including RT as shown in Fig. 5. The effect of FLS/TFA% at different temperatures shows similar trends, i.e. an increase in the strength ratio as the FLS/TFA% increases up to FLS/TFA =20% and after that it decreases to approach that at 0% FLS/TFA at FLS/TFA% equal to 40%. Also it is clear that the strength ratio increases as the exposed temperature increases especially at temperatures of 600 and 700°C for all FLS/TFA %. As an example for FLS/TFA% equal to 20%, the strength ratio reached 1.12 at 200°C, 1.18 at 500°C and 1.60 at 700°C. The FLS shows some of hydration reactivity, which allows it to behave as a pozzolanic when it was mixed with cement. So, using of lead-slag as aggregate enhances a type of aggregate cement paste interface. The decrease in the strength with further increase in the replacement of sand by FLS may be due to the fact that by increasing the fine lead- slag aggregate without the equivalent required amount of cement to achieve pozzolanic hydration, an adverse effect on the bond in the matrix is occurred [9]. At high temperatures, the reduced amount of Ca(OH)2 due to the pozzolanic effect of FLS increase the strength ratio at those temperatures, which otherwise results in strength loss and disintegration [16]. Photo.1 shows the crack pattern of the mortar specimens after exposed to temperature of 700°C for FLS/TFA equal to 0 and 20%. A wide crack is observed on the specimen surface for FLS/TFA% equal to 0 compared to a very narrow surface cracks in the case of FLS/TFA equal to 20%.

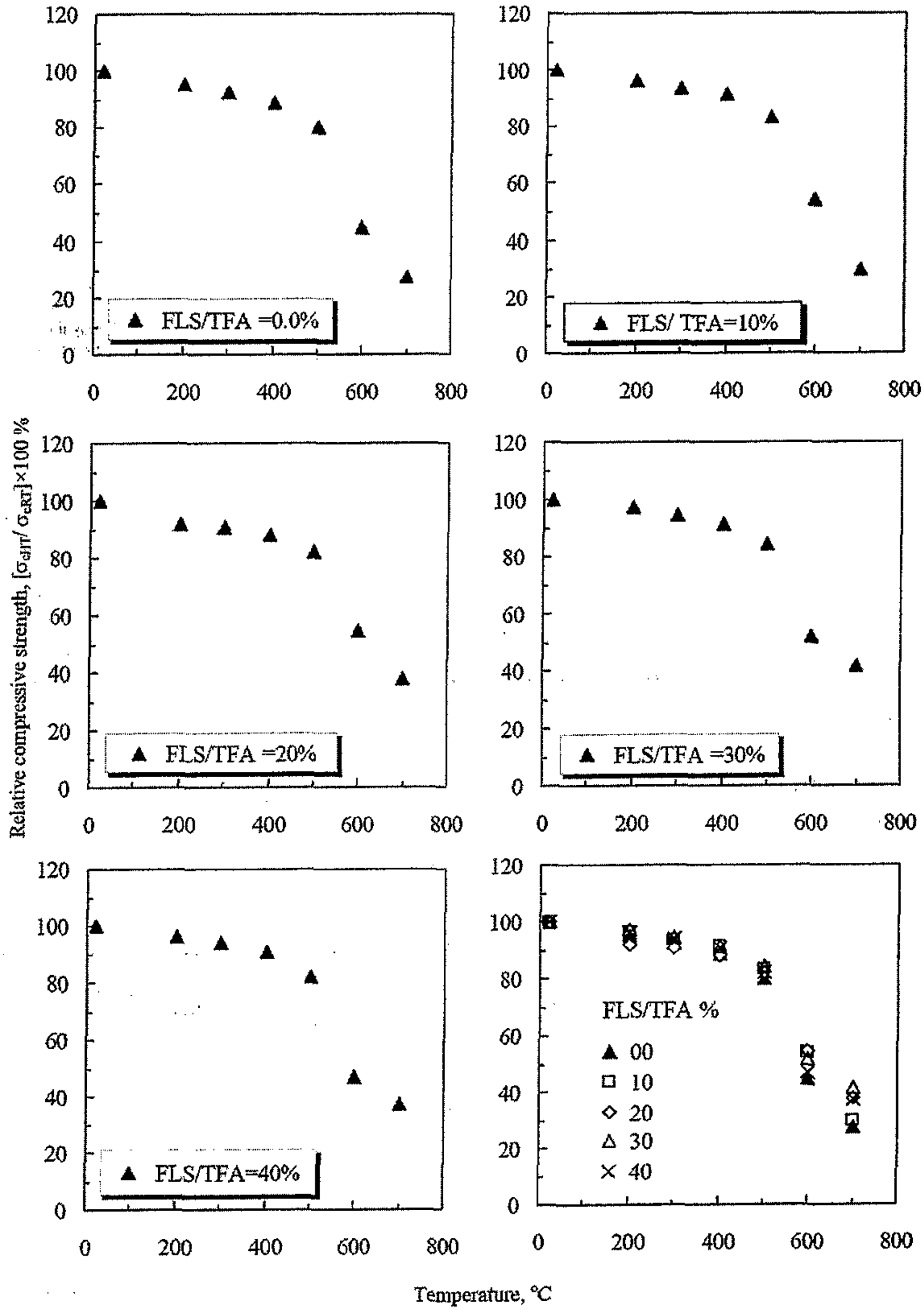


Fig. 4 Relative compressive strength against temperatures for different FLS/TFA%.

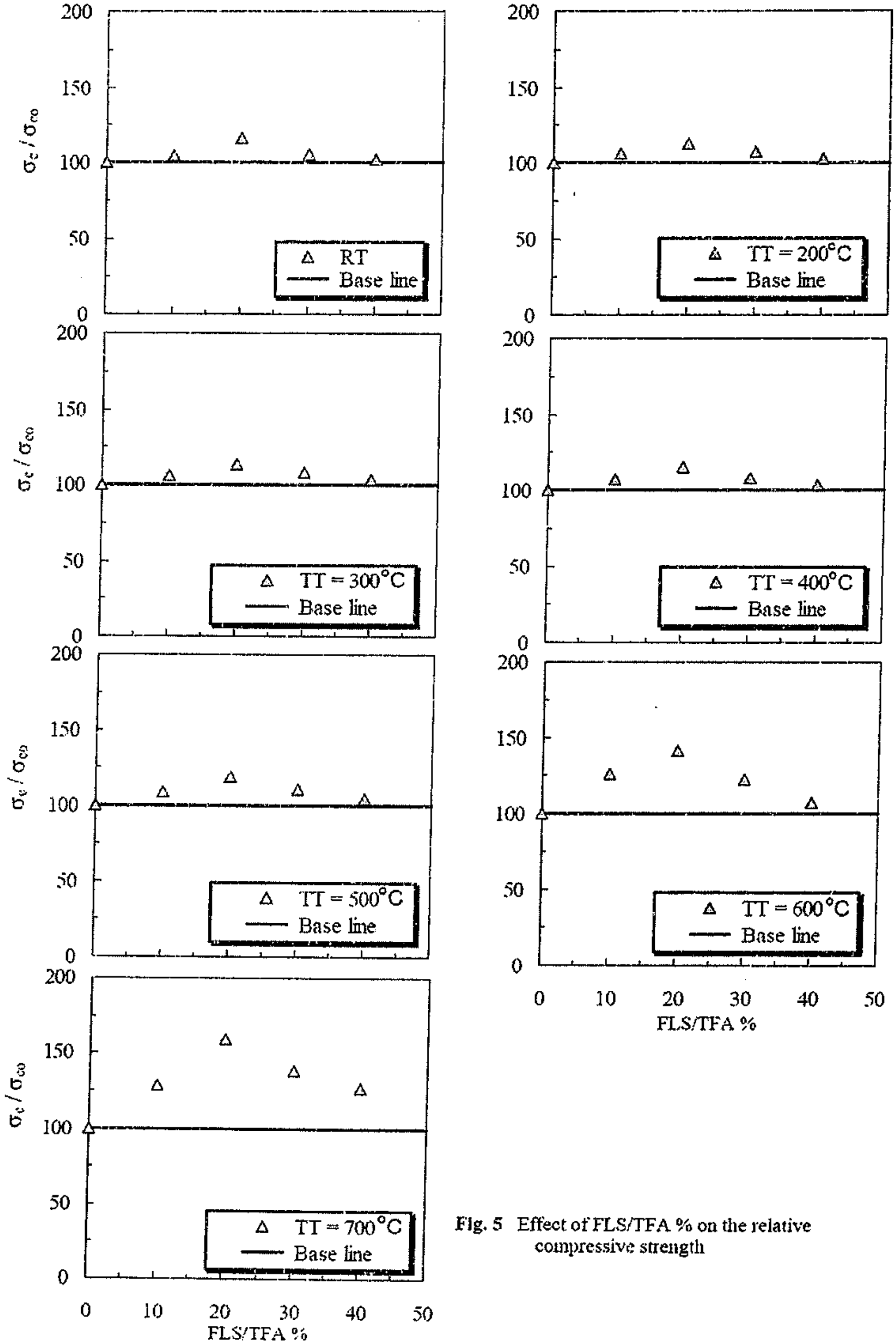
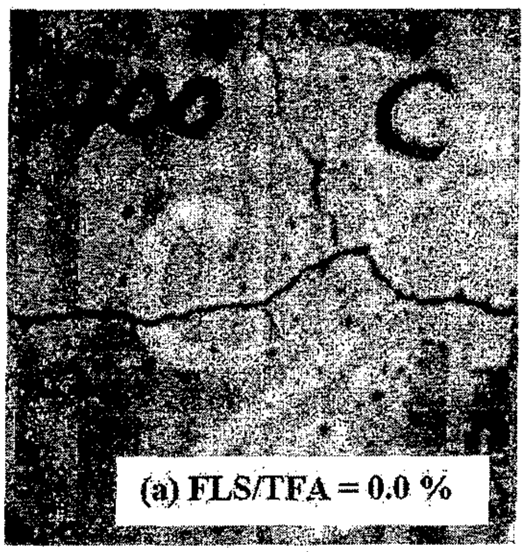


Fig. 5 Effect of FLS/TFA % on the relative compressive strength



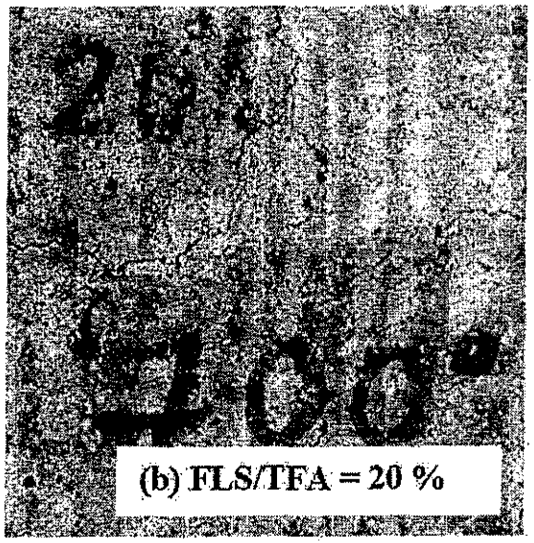


Photo. 1 Crack pattern of mortar specimens after heating to 700 oC for
a) FLS/TFA = 0.0 % and
b) FLS/TFA = 20%.

Abrasion Resistance

The effect of high temperature on the abrasion resistance of mortar fabricated by partial replacement of sand by different percentages of FLS/TFA is shown in Fig. 6. The abrasion resistance defined by the wear rate (WR) is expressed as the weight loss of the tested specimen divided by the area of the surface exposed to wear. This is of a physical meaning, since abrasion is a surface property that defines surface layer characteristics. The exposed surface area for all specimens is constant and equal to the area of a circle having a diameter of 25 mm. The unit now is gm/mm^2. Fig. 6 shows the relation between the relative wear rate (wear rate of specimens exposed to heat multiplied by 100 and divided by that of the unheated specimens at the same FLS/TFA%). The figure shows increases in the relative wear rate with increasing temperature for all FLS/TFA%. This means a decrease in the abrasion resistance with increasing temperature and the relation is approximately linear. This trend is similar to that of compressive strength.

To reflect the effect of FLS/TFA% of the abrasion resistance of mortar at different temperature, the wear rate ratio (the ratio of the wear rate of mortar specimen containing FLS to that of 100% sand at the same temperature) is drawn in Fig. 7 against FLS/TFA% for different temperatures considered. The presence of FLS enhances the abrasion resistance of mortar specimens up to 20% replacement and after that the effect decreases until it approximately match that of 100% sand at FLS/TFA equal to 40%. The role of FLS replacement is more pronounced at high temperatures above 500°C.

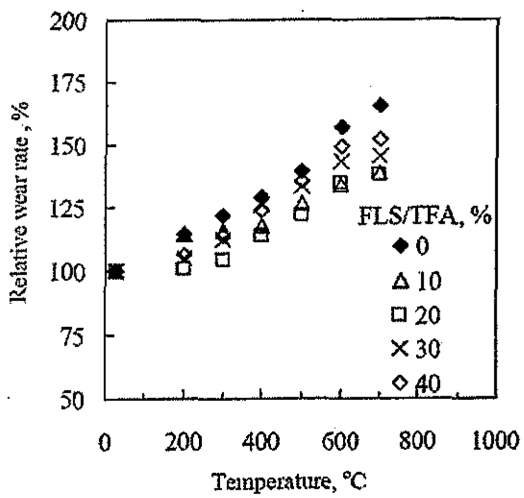


Fig. 6 Effect of high temperature on the relative abrasion rate for different FLS/TFA %.

The presence of FLS, which behaves as a pozzolanic material reacts with the hydration products forming and thus enhances cement aggregate interface and leads to dense structure composed of irregular grains and hydrated products attach to the aggregate surface strongly. This improves the resistance of the mortar to abrasive wear. With the increase in FLS above 20%, the remaining un-reacted FLS behaves as filler and which can easy leave the surface of the specimen during abrasion.

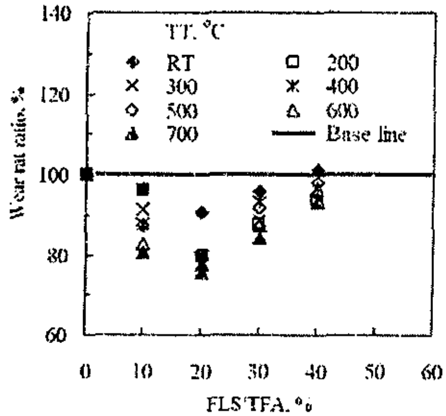


Fig. 7 Effect of FLS/TFA % on the wear rate ratio at different high temperatures.

4. CONCLUSIONS

1. The compressive strength of fine lead slag mortar decreased gradually with increasing temperature up 500°C and after that temperature the strength decreased markedly.
2. With increasing fine lead slag percent as a partial replacement of sand, the compressive strength increased up to fine lead slag percent of 20 % and after that it decreases but still higher than that of 100 % sand at 40 % fine lead slag.
3. The presence of fine lead slag played a vital role in enhancing the strength ratio of lead slag mortar compared to those of sand mortar especially at high temperatures above 500oC.
4. The abrasion resistance of plain and lead slag mortar decreased linearly with increasing high temperature.
5. The highest abrasion resistance was that of mortar specimens of 20% fine lead slag.
6. The presence of fine lead slag enhanced the abrasion resistance of plain mortar and the rate of enhancement is more pronounced at temperatures above 500oC.

5. REFERENCES

[1] Jepsen, M. T., Mathiesen, D., Munch-Petersen, C., Bager, D., (2001), Durability of resource saving "Green" type of concrete, In: Proceedings of FIB – Symposium on concrete and environment, Berlin.

[2] Monce, N. and Ashfaq, K., (2001), Cementitious composites containing recycled tire rubber: an overview of engineering properties and potential applications, Cement Concrete Aggregate, Vol. 23, pp. 3–10.

[3] Basri, H. B., Mannan, M. A., Zain, M. F. M., (1999), Concrete using waste oil palm shells as aggregate, Cement Concrete Research, Vol. 29, pp. 619–22.

[4] Padmini, A. K., Ramamurthy, K., Mathews, M. S., (2001), Behaviour of concrete with low-strength bricks as lightweight coarse aggregate, Magazine of Concrete Research, Vol. 53, pp. 367–375.

[5] Palmquist, S. M., Jansen, D. C., Swan, C. W., (2001), Compressive behavior of concrete with vitrified soil aggregate, ASCE J. Mater. Civil Eng., Vol. 13, pp. 389–394.

[6] Binici, H., (2007), Effect of crushed ceramic and basaltic pumice as fine aggregates on concrete mortars properties, Construction and Building Materials, Vol. 21, pp. 1191–1197.

[7] De Brito, J., Pereira, A. S., Correia, J. R. (2005), Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates, Cement & Concrete Composites, Vol. 27, pp. 429–433.

[8] Metwally, M. E. A, Seleem, M. H., Balaha, M. M., and Abd El-Rahman, H. (2005), Utilization of slag produced from recycling of spent lead-batteries as concrete aggregate, Alexandria Engineering Journal, Vol. 44, pp. 883-892.

[9] Penpolcharoen, M. (2005) Utilization of secondary lead slag as construction material, Cement and Concrete Research, Vol. 35, pp. 1050-- 1055

[10] Bilirb, İ. Y. T, and Özkanc, Ö., (2007), Durability of concrete incorporating non-ground blast furnace slag and bottom ash as fine aggregate . Building and Environment, Vol. 42, pp. 2651–2659.

[11] American Society for Testing and Materials, (1989) "Test method for abrasion resistance of horizontal concrete surfaces", ASTM C779-89, Annual Book of ASTM Standard, ASTM, 4.02, p 359.

[12] El-Shihy, A. M., Seleem, M. H., Shoaib, M. M. Badawy, A. A. M, and Gabal, A. E. K. (2004) Effect of elevated temperatures on the mechanical and physico-chemical behavior of normal, high strength and light weight concrete. Mansoura 4th Int. Engineering Conf,. 20-22 April, C51-C59.

[13] Hewlett, P. C., (1998), Lea's chemistry of cement and concrete. Co-published in North Central and South America by Jhon Wiely & Sons Inc., New York and Toronto, 4th edition.

[14] Zang, B., Bicanic, N., Pearce, C. J. and Balabanic, G. (2000), Residual fracture properties of normal and high-strength concrete subjected to elevated temperature. Magazine of Concrete Research, Vol. 52, No.2, pp. 123-136.

[15] Wei-Ming Lin, Lin, T. D. and Powers-Couche, (1996), Microstructures of fire-damaged concrete. ACI, Material Journal, Vol. 93, No. 1, pp. 199-205.

[16] Chan, S. Y. N. Peng, G. F., Anson, M., (1999) Residual strength and porestructure of high-strength concrete and normal-strength concrete after exposure to high temperatures, Cement &. Concrete. Composite, Vol. 21, pp. 23–27.