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Thermal properties of sand modified resins used for bonding CFRP to concrete substrates

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Abstract

This study is an experimental investigation about the thermal properties of adhesive before and after mixing with fine sand. The results show that such an addition significantly improves the thermal characteristics, such as reducing the initial and the final shrinkage, reducing the heat of the reaction, coefficient of linear expansion, and the coefficient of the thermal conductivity. Also, such an addition leads to a reduction in the adhesive cost and a small increase in the compressive strength and the modulus of rupture. The ratio of the fine sand to the adhesive equal to 1 is considered the best in terms of the cost reduction, maintaining workability, as well as maintaining the mechanical properties.
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Keywords: Concrete; Epoxy; FRP; Sand; Thermal

1. Introduction

The high strength-to-weight ratio, electro-chemical corrosion resistance, and orthotropic properties of fiber-reinforced polymer (FRP) have made them attractive to civil engineers, faced with deteriorating infrastructure. Fiber wrapping is perhaps one of the most successful applications of FRP, simply because the strength enhancement is accompanied by a considerable cost savings over the traditional retrofitting alternatives (Mirmiran et al., 1999).

Epoxy adhesive is used to paste the fibers on the concrete or steel, and is available in several types according to the manufactures. It usually consists of two parts, the first is called ‘‘Resin” and the second is called ‘‘Hardener”. Strengthening the concrete structure with the Epoxy bonded carbon fiber reinforced the polymers ‘‘CFRP” has been proven to be a good strengthening technique. However, there are some disadvantages with such a technique, such as diffusion closeness, thermal incompatibility to the base concrete, working environment and the minimum application temperature (Täljsten and Blanksvärd, 2007).

Sen et al. (2001) have studied the effect of the climate in Florida, throughout the year, on the concrete strengthening by the ‘‘CFRP”. Their work includes the effects of air temperature and the cycles of moisturizing and drying. They have proved that the carbon fiber and the epoxy adhesive are highly resistant to weather conditions.

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Gao et al. (2004) have studied the effects of the adhesive properties on the structural performance of the reinforced concrete beams, strengthened with carbon fiber reinforced polymer (CFRP) strips. The Epoxy adhesive which is modified by liquid rubber of different content was used to bond the CFRP strips. Four point bending experiment was carried out on RC beams. The results have shown that the different CFRP strips, 0.22 and 0.44 mm thick, have resulted in a transition of failure mechanism from interfacial debonding, along the CFRP-concrete interface, to concrete cover separation, starting from the end of the CFRP strips in the concrete. Moreover, it is suggested that no matter how the interfacial debonding or concrete cover separation will be, the rubber modifier enhances the structural performance by increasing the maximum-load carrying capacity and the corresponding ductility, compared with the beams, bonded with a net Epoxy resin.

Camata et al. (2007) have studied the effect of exposing concrete models, strengthened by plates of carbon fiber, to heating cycles with temperatures up to 1000 °C. The study has proved that all kinds of used Epoxy have significantly affected the heating cycles.

Klamer et al. (2008) have, also, studied the effect of temperature on the reinforced concrete beams, strengthened by CFRP. Test results have shown that, compared to room temperature, the type of failure and failure load of the beams tested at 50 °C were not significantly affected. At 70 °C, the type of failure changed for one of the beams from failure in the concrete adjacent to the concrete adhesive interface to failure exactly in the concrete-adhesive interface. The failure loads of the beams tested at 70 °C were not significantly affected compared to room temperature, except for the beam with a relatively short laminate length. For this beam, the load capacity is expected to be mainly related to the capacity of the end anchorage zone, which was negatively affected by the effects of the elevated temperature.

Blanksvärd (Blanksvärd, 2009) has used adhesive material consisting of reinforced polymer mortar (Polymer, mortar, superplasticizer, and fibers) instead of epoxy. His experiments have proved that this new adhesive is efficient for the CFRP. But, this material is expensive and difficult to use because of the difficulty to control mixing ratios for many components. Therefore, this adhesive can be used as crack reinforcement in prefabricated concrete elements.

Cabral-Fonseca et al. (2011) have studied the effect of environmental conditions on three different types of epoxy used in strengthening or rehabilitating concrete structures. The models have been immersed in seawater and in alkaline solutions for 18 months at a temperature of 40–60 °C. The mechanical properties and the weight loss of the samples have been measured. The study has proved that the epoxy is greatly influenced by the environmental conditions, being immersed in seawater and alkaline solutions. Büyüköztürk et al. (2012), in turn, have studied the effect of moisture on the cohesion between epoxy and concrete, and the tests have shown that humidity reduces cohesion between the epoxy and the concrete.

Al-Safy et al. (2012) have studied the thermal and mechanical properties of nanoclay-modified adhesives for use in civil engineering applications. Differential Scanning Calorimetry (DSC), X-ray diffraction (XRD) and Transmission Electron Microscopy (TEM) were used to characterize the adhesive structure. The glass transition temperature (Tg), measured by DSC, was found to decrease with nanoclay addition. Measurements from XRD and TEM have identified an intercalated/exfoliated structure of the nanoclay, nanomer I.30E in the epoxy matrix. The adhesive tensile strength showed a reduction with the addition of nanoclay at elevated temperatures. However, improvement in the tensile modulus was found for all nanoclay addition. The bond-loss temperature of CFRP/concrete systems with a modified adhesive was observed to be lower than that for the control (0% NC), using adhesion (pull-off) tests at elevated temperatures. Also these materials were very expensive.

Nguyen et al. (2012) have studied the effects of UV on the bond between steel and CFRP. Specimens (epoxy adhesive, CFRP laminates, and steel/CFRP adhesively bonded joints) were exposed to UV for various time periods while identical reference specimens were exposed to only thermal environments without UV. They have found that the exposure to UV does not influence the tensile strength of CFRP composites. The tensile strength of the adhesive is reduced by 13.9% while modulus has shown a significant increase by 105% after 744 h of exposure. The tensile modulus of adhesive, exposed to only thermal environment, has also increased by 38%, considerably less than that induced by UV exposure. The UV exposure has also led to a decrease in the joint strength. An increase in stiffness is caused by the temperature effect rather than the UV rays.

The present study aims at enhancing the properties of adhesives, used for bonding FRP or others by mixing a well-known adhesive with a cheap material (fine sand). The sand is cheap compared to the price of epoxy which represents almost 2000–3000 times the price of sand. So, the proposed method leads to a large reduction in the cost of the adhesive (sand price consider negligible) in addition to improving their properties. Some mechanical properties and thermal properties for adhesive, with or without fine sand, were mainly investigated to prove the efficiency of this addition which is, in fact, intended to improve the adhesive properties and saving the cost.

2. Experimental works

2.1. Materials

– *Adhesive:* Sikadur®-330 from 330 is used. The properties of the adhesive are shown in Table 1.

Table 1
Properties of Sikadur®-330.

Properties	Description
Density	1.31 kg/L mixed (A + B) at (+23 °C)
Mixing	1:4 (A:B) by weight
Application temperature	+15 °C to +35 °C
Tensile strength	(Curing 7 day, +23 °C) = 30 N/mm^2
Flexural modulus	(7 day, +23 °C) = 3800 N/mm^2
Tensile modulus	(7 day, +23 °C) = 4500 N/mm^2

– *Fine-sand:* Granular sand passes from 300 μm sieve and remaining on a 75 μm sieve is used. Sand is washed well and dried before use. The specific gravity of sand is equal to 2.41, absorption is equal to 2.13, and the sulfate content after washing is equal to 0.045%.

2.2. Mixing

The Adhesive consists of two parts namely resins (Part A) and hardener (Part B). They are to be mixed together by 1:4 ratio. The fine sand must be mixed with either part A or B before mixing A and B together. After mixing the sand with the mixture of A and B, the workability is largely reduced and the reason for this is the interaction of the adhesive parts prevents the penetration of sand. Hence, the sand must be added to part A or B before mixing A with B. Also, adding sand to part A or B reduces the temperature of reaction as the results will show.

2.3. Consistency of adhesive

The consistency of adhesive is expressed as an adhesive flow, determined according to the procedures of ASTM C 1437 (C1437-15, 2015) by a flow table. The flow table which is used for computing the consistency of cement mortar is suggested here by authors for computing the consistency of adhesive. Epoxy adhesive is poured in a truncated cone. The cone is placed on a flow table which its top can be raised and dropped through to a certain height by means of a rotating cam. The mold is removed from the adhesive, and the table is dropped 25 times in 15 s (see Fig. 1). The flow is measured as the result increases in the average base diameter of the adhesive mass. It is measured as a percentage of the original diameter. The author also suggests computing the initial flow (after removing the truncated cone and before the dropping of the table). This value is not important and is not sensible for cement mortar but it's valuable for epoxy.

2.4. Thermal properties

(A) The temperature is monitored for the adhesive interaction with or without the addition of fine sand.

(B) Measuring the shrinkage of the adhesive prisms from the beginning of the mixing process till reaching the stability of the shrinkage. Measuring the coefficients of linear expansion of the prisms after the final hardening (7 days age) when the temperature raises by 40 °C of the laboratory and measuring the shrinkage when the temperature reduces by 40 °C. Also, the shrinkage is measured after using the adhesive to fix CFRP, where they are strengthening the prisms concrete and fixing demec point in the adhesive to measure the shrinkage from the beginning of the installation and for several days until the shrinkage is stable.

(C) Measure the coefficient of thermal conductivity of different addition ratios of fine sand and compare it with the adhesive cubes without fine sand. The method of measuring the thermal conductivity coefficient is according to ASTM and according to the steps outlined by Abdulla et al. (2013).

2.5. Mechanical properties

Casting adhesive cubes (40 × 40 × 40 mm) and prisms (40 × 40 × 160 mm), and adding different ratios of sand, as shown in Table 2. The samples are left for seven days to dry and harden permanently. Compressive strength and modulus of rupture for prisms have been measured. Comparison between the characteristics of the neat adhesive and adhesive, mixed with fine sand, has been done.

3. Results and discussion

3.1. Mixing

As noted earlier, sand's mixing must be done with one part of the adhesive (resin or hardener) to ensure getting a good workability and to reduce the temperature of reaction. After mixing sand with one part of the adhesive, the workability of sand is significantly reduced and the penetration of the adhesive inside the CFRP will be affected along with the cohesion of the concrete or cement mortar.

3.2. Consistency of adhesive

The flow of mixing decreases when the fine sand ratio is increasing because the mixture ability E5 (sand/adhesive ratio = 1.5) in the flow is unacceptable (see Table 1), and the compressive strength will start decreasing as will be explained later in the mechanical properties. The optimum ratio for sand to adhesive is 1 (mix E4), where E4 has a good workability, thermal, and mechanical properties as will be explained later.

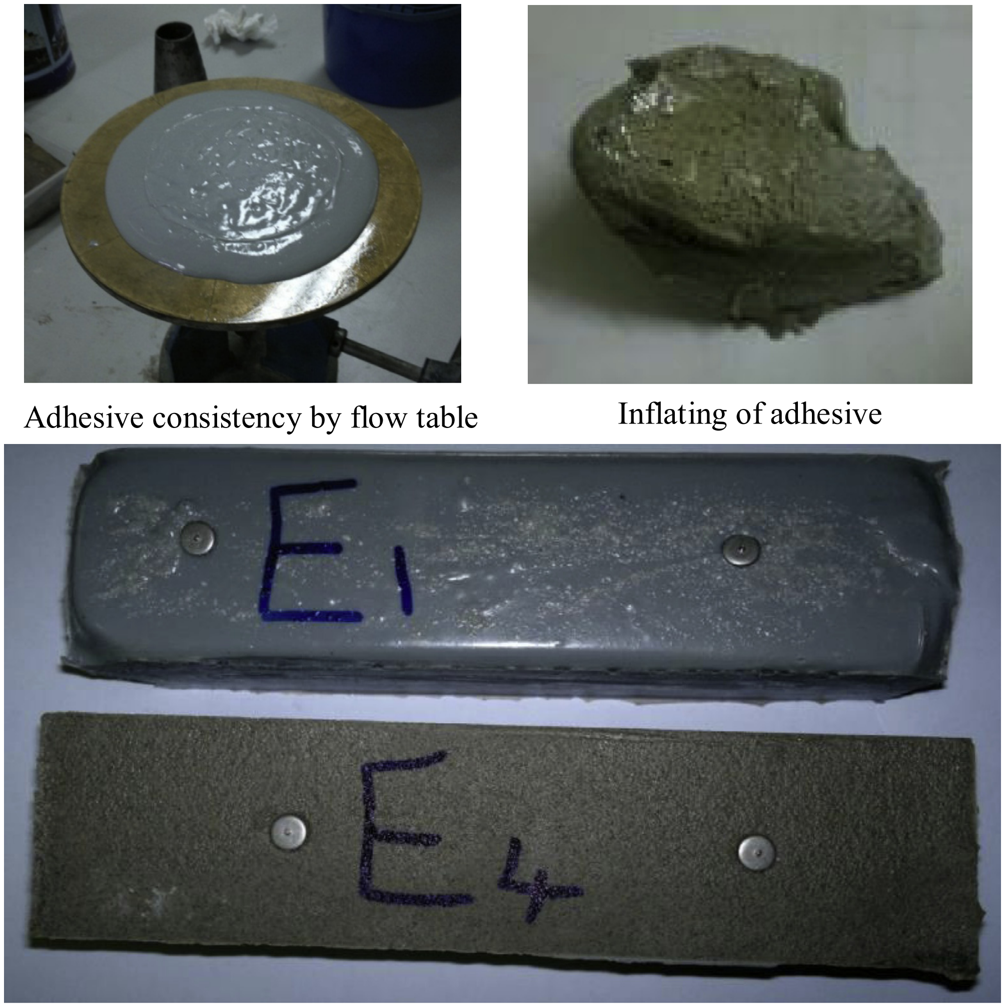

Figure 1. Consistency, instant inflating, and visible shrinkage of adhesive.

Table 2
Mixing ratio and flow values for adhesive.

Sym	S/E	Flow (%)	
		Initial	Final
E1	0	135	195
E2	0.25	126	187
E3	0.5	119	183
E4	1	111	176
E5	1.5	101	141

S/E = sand/epoxy ratio by weight.

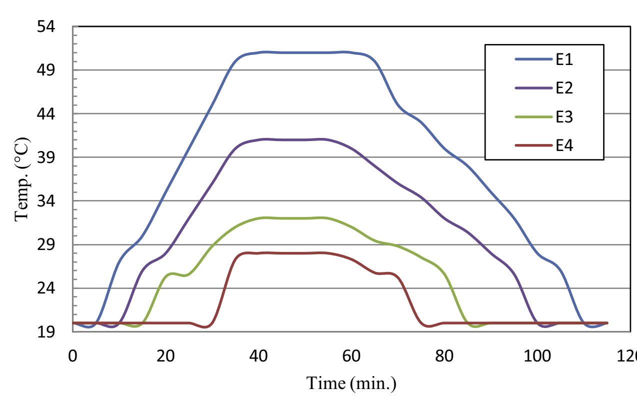

Figure 2. Adhesive reaction temperature.

3.3. Thermal properties

– *Expansion and shrinkage:* mixing two parts of adhesive produces a high temperature reaction, and a large expansion and shrinkage during the first hour of the reaction. One of the important observations is that it is not possible to mix a large amount of epoxy for the high heat of the reaction will lead to inflating, rapid hardening effects, as well as losing strength (see Fig. 1). Fig. 1 shows the great shrinkage that occurs in the adhesive prisms compared to the invisible shrinkage in the adhesive prisms, mixed with fine sand. Fig. 2 illustrates the increasing in temperature after the mixing process and clearly demonstrates the importance of mixing

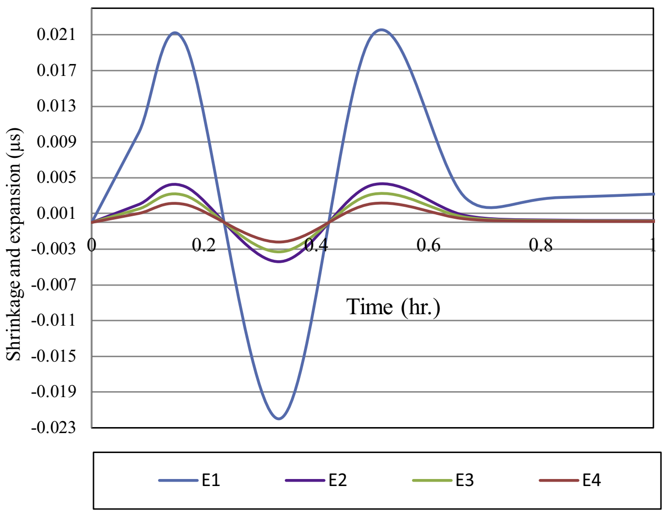

Figure 3. Initial shrinkage and expansion of adhesive.

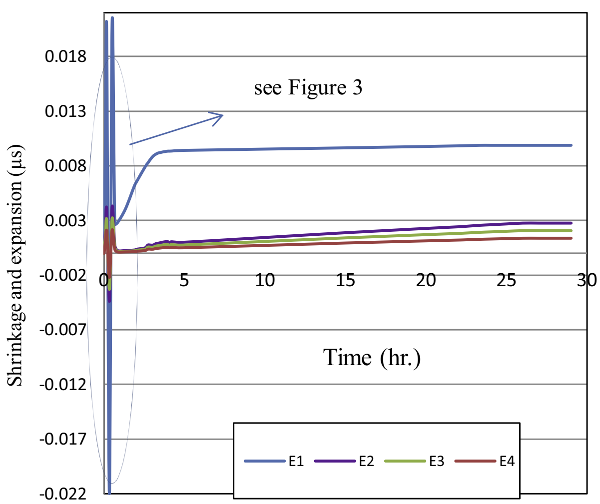

Figure 4. Initial and final shrinkage of adhesive.

fine-sand with the adhesive where it leads to a reduction in the maximum temperature by 20%, 36%, and 44% when using the proportion of sand in the adhesive by 0.25 and 0.50 and 1 of the weight of adhesive, respectively.

Figs. 3 and 4 show a shrinkage and an expansion of the adhesive from 0 to 29 h. of the mixing age. There is a shrinkage and an expansion in the adhesive during the first hour of mixing due to the rise in temperature in a short period. The shrinkage stops after approximately 24 h. The figures clearly show that the addition of fine sand leads to a significant reduction of shrinkage and expansion as it leads to a reduced initial ultimate shrinkage by 96.4%, 97.3%, 98.2% and a final ultimate shrinkage by 72.0%, 79.01%, 86.3% when using the proportion of sand in the adhesive in the following ratios 0.25, 0.50, 1 of the weight of adhesive, respectively.

Fig. 5 illustrates the expansion and contraction of the adhesive prisms which were left for 7 days with an increase

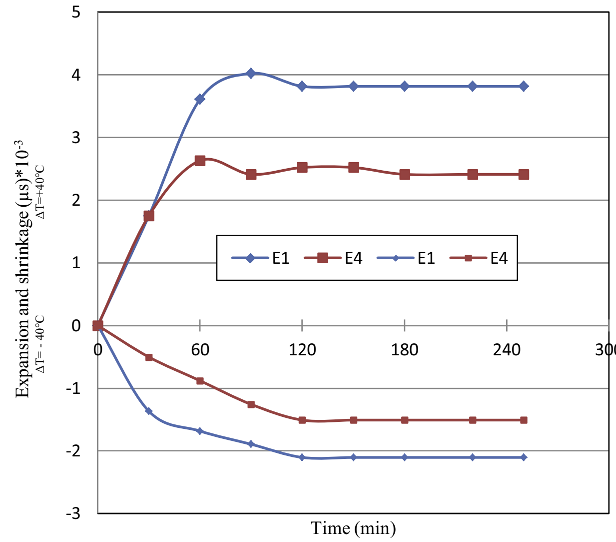

Figure 5. Expansion and shrinkage of hardened adhesive prism at 7-days age.

Table 3
Coefficients of linear expansion and thermal conductivity for mixes.

Mixes	Thermal conductivity k (W/m °C)	Coefficients of linear expansion (1/°C)
E1	0.62	0.09541
E2	0.61	0.08451
E3	0.59	0.07311
E4	0.58	0.06030

and decrease in the temperature by 40 °C of laboratory temperature. Fig. 5 further shows that the addition of sand to the adhesive reduces the expansion by 36.7% and shrinkage by 28.3%. Adding sand enhances the coefficient of linear expansion and the coefficient of thermal conductivity for the adhesive (see Table 3).

As has been noted previously, the shrinkage of the adhesive after being used to fix CFRP on the concrete prisms has been measured. Fig. 6 illustrates the way and places that install the demec point and the relationship between time and shrinkage. The prism which is strengthened by the adhesive has shown a large shrinkage and expansion before stabilizing after 90 min. Later on, shrinkage starts increasing on a regular basis, but deteriorates to zero after 90 h. After that, it starts expanding to reach its highest value age which is 97 h. Finally, the expansion settles. Prisms with adhesive, fortified with sand (E4), did not show a big shrinkage, and then it settled downturn after about 40 min, without any expansion.

3.4. Mechanical properties

– *Compressive strength:* Fig. 7 shows the compressive strength test results for the adhesive cubes with different percentages of fine sand. Results clearly show that the

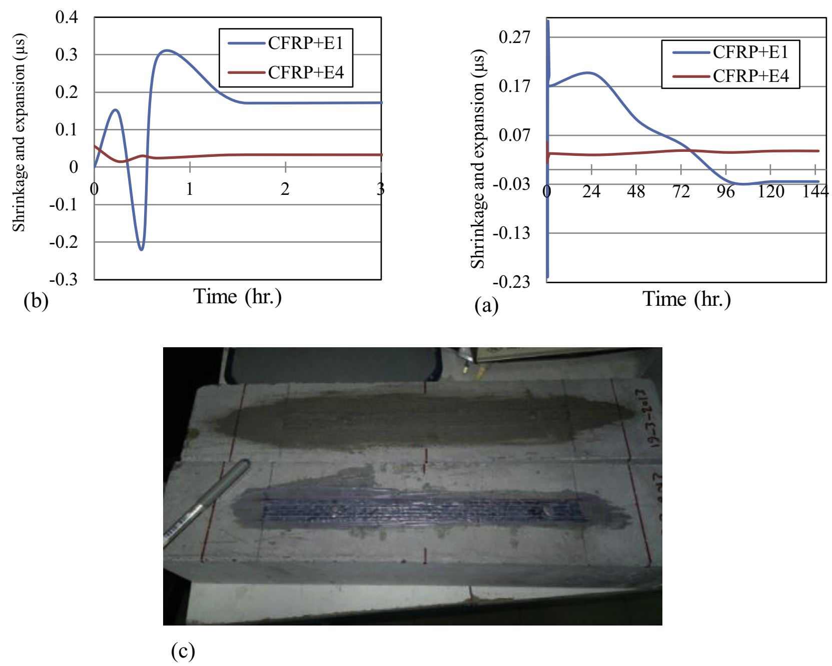

Figure 6. Shrinkage of concrete prisms strengthening by CFRP. (a) 0–144 h. (b) 0–3 h. (c) Photo of prism after fixing demec points.

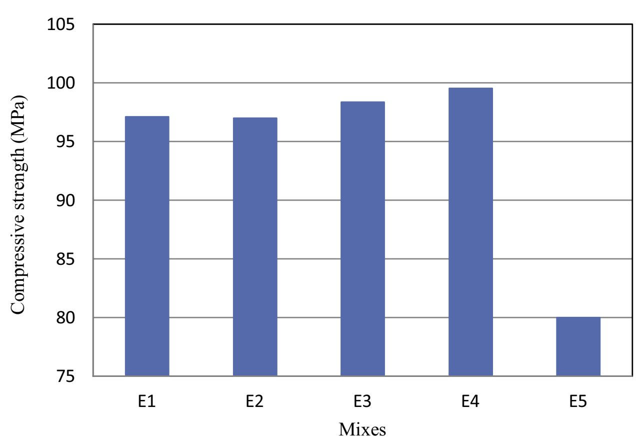

Figure 7. Effect of fine-sand ratio on the adhesive cubes compressive strength.

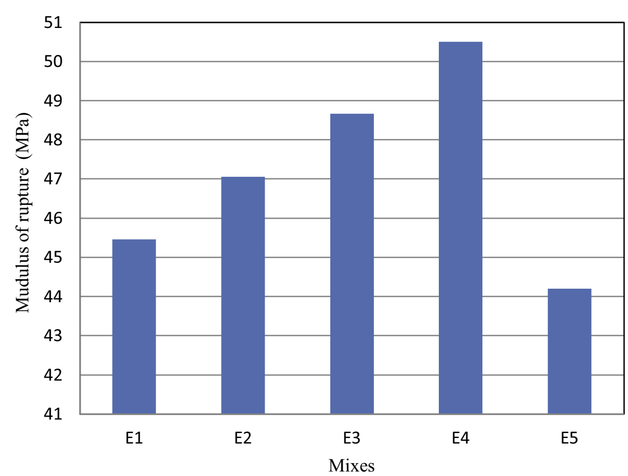

Figure 8. Effect of fine-sand ratio to the modulus of rupture of adhesive prisms.

increase in the proportion of sand increases the compressive strength and the best ratio of sand to adhesive material is the ratio of 1 (mix E4) where the sand is 50% of the total weight of the adhesive. When the ratio of fine-sand to adhesive increases to more than 1, it will affect the workability and strength. Although the ratio of addition (mix E4) gives a small increase in the compressive strength which is equal to 2.5%, the addition of sand constitutes a reduction in the cost of the adhesive to almost a half where the price of sand is negligible compared to the price of the adhesive. Thus, when the sand's total weight forms 50% of adhesive, it means a reduction in the cost to the half and an improvement in the thermal characteristics.

– *Modulus of rupture:* Fig. 8 shows the relationship between the modulus of rupture and the added ratio. It also shows that the best ratio of sand to adhesive is 1, namely the E4 mixes.

4. Conclusions

1. Fine sand must be mixed with one part of the adhesive (resin or hardener) to get a good workability and a decrease in the reaction of temperature.
2. The flow of mixing decreases when fine sand ratio is increasing, and the optimum weight ratio for sand to adhesive is 1.

3. Mixing two parts of the adhesive (without the fine sand) produces a high temperature reaction and a large expansion and a shrinkage during the first hour of the reaction which lasts for 24 h. One of the important observations is that it is not possible to mix a large amount of epoxy because the high heat of the reaction will lead to an inflating, rapid hardening, and a lose in the strength.
4. The heat of reaction in the adhesive without fine sand is increased directly after the mixing process.
5. Adding fine sand to the adhesive reduces the heat of reaction, expansion and shrinkage for both a short and a long time, and prevents the inflating and rapid hardening due to mixing a big amount of epoxy.
6. Adding fine sand to the adhesive reduces coefficients of linear expansion and thermal conductivity.
7. Adding fine sand to the adhesive increases adhesive compressive strength and modulus of ruptur.
8. Further research is needed to investigate the tensile and bond strength of the sand-modified epoxy.

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