International Journal of Integrated Engineering, Vol. 6 No. 1 (2014) p. 13-16

Properties of Structural Lightweight Concrete Filled with Palm-Based Polyurethane

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Abstract: Four experiments were conducted to characterize the properties of palm-based polyurethane (PU) foam in lightweight concrete. The PU foam was synthesized from palm kernel oil-based polyol reacted with 2, 4-methylene diphenyl diisocyanate. Polyurethane as lightweight aggregate was mixed with ordinary cement, sand, and water to form lightweight concrete. The microstructure of PU aggregate can be accessed from optical micrographs. Density, compressive strength, distribution of fine aggregate, and the interfacial zone were also investigated. The result showed that palm-based lightweight concrete has excellent compressive strength (17.5 MPa), and fulfilled the minimum strength requirement for structural concrete. Palm-based lightweight concrete with 0.6 w/c ratio and 3% w/w PU system achieved 1770 kg/m^3 presented uniform dispersion of aggregate and excellent mechanical bonding.

Keywords: polyurethane, palm kernel oil, lightweight concrete, compressive strength, interfacial zone

1. Introduction

Lightweight concrete can be produced by introducing lightweight aggregate, such as expanded clay, expanded polystyrene, polyurethane, and so on [1,2]. Within the wide range of plastics materials, the manufacture of polyurethane (PU) by polyisocyanate/ polyol reaction occupies a special place because of its broad spectrum of applications. The properties of high molecular polyurethane products can be controlled chemically and physically in such a manner that different properties are achieved. In general, most polyols used in the polyurethane industry are petroleum-based, where crude oil and coal are used as starting raw materials. However, the prices of these polyols are high because of the high technology processing system.

This study presents the usage of a natural and sustainable material, palm kernel oil polyol (PKO-p), as a substitute in the polyurethane industry. Polyurethane foam is a particularly good insulator because of its thermal resistance value (R-value). Badri [3] had successfully produced and developed polyurethane for wide applications, such as rigid foam, elastomer, coating, adhesive, and sealant. Usage of PU polyol in the making of concrete has not been reported elsewhere. The PU systems consist of PKO-p and 2, 4-methylene diphenyl diisocyanate (crude MDI). The molecular weight and the functionality of polyols affect the resulting foam properties. Polyisocyanates act as the jointing agent of polyols. Therefore, urethane and related foams are recognized as building block polymers [4].

In the meantime, the palm-based lightweight concrete for this study exclusively considers structural lightweight concrete, that is a mixture of ordinary cement, fine sand, water, and polyurethane particles, as fine or lightweight aggregates less than 5 mm [5,6]. Normal concrete typically has density around 2400 kg/m^3, whereas lightweight concrete (LWC) has a density ranging from 800 kg/m^3 to 1800 kg/m^3. Minimum compressive strength for structural lightweight concrete at 28-days was 17 MPa [7,8].

In the present study, an attempt was made to examine the development and formulation of polyurethane and lightweight concrete. The density, compressive strength, and the interfacial zone within the hardened cement paste using optical micrographs were investigated.

2. Experimental Procedures

The ratio of PKO-p resin to crude MDI was fixed to 1:1 and mixed using an overhead stirrer at a speed of 1000 rpm for 10 second to form the polyurethane foam through polymerization process. The mixture was then poured into a screw-tight mold, and was allowed to cure for 10 minute. Rigid PU foam was demolded and conditioned at room temperature for 16 hours prior to characterizations. PU foam which functioned as the lightweight aggregate in concrete was ground and sieved up to 5 mm diameter.

An attempt to identify the formulation of palm-based lightweight concrete less than 1800 kg/m^3 was conducted. Notably, the most effective and dominant parameters that

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affect the density and compressive strength are loading percentage of PU and water-cement ratio (w/c) [9]. Therefore, loading percentage of PU aggregate and w/c ratio were set as varying variables. The optimization study indicated that 0.6 w/c ratio with 3% weight by weight (w/w) PU system were optimum ratio and processing composition. Palm-based lightweight concrete was prepared by integrating cement, sand, and w/c at a ratio of 1:2:0.6 in a drum mixer. About 3% (w/w) of PU system were mixed into the concrete mixture for another 3 minute until uniformly distributed. The specimens were casting in a steel mold of 100 mm × 100 mm × 100 mm dimensions. The density and compressive strength were determined.

3. Characteristic

Density of PU rigid foam (kg/m^3) was determined following BS4370: Part 1: 1988 Method 2 and calculated using the equation of mass (kg) divided by volume (m^3). The PU was prepared by molding technique into a cubic mold of 50 mm × 50 mm × 50 mm in dimensions. Three replicates were carefully weighed using an analytical balance and the mass was recorded.

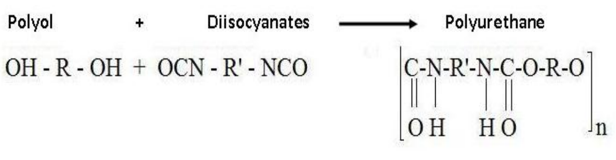
The density of the lightweight concrete was also calculated by mass per unit volume following BS EN12390: Part 7: 2002 standard. Three specimen were carefully weighed using an analytical balance and the mass was recorded.

Compressive strength test was conducted according to BS EN 12390: Part 3: 2001 standard. The test was carried out using Autocon 2000 Universal Testing Machine with a loading rate 7.0 kN/s. The specimens were prepared by molding technique into a cubic mold of 100 mm × 100 mm × 100 mm in dimensions. The specimens were tested based on exposure time of 7, 14, and 28-days. The compressive stress and load peak data were recorded. The compressive strength was calculated using equation of maximum load at failure (N) divided by area (m^2).

The optical micrograph analysis was carried out to study the dispersion and interfacial adhesion between PU systems and cement paste. The analysis was carried out using a Dino-lite Microscope Pro model AM-413T. The dried samples were cut and scanned at 500× magnifications.

4. Results and Discussion

Polyurethane is produced through the reaction between polyhydroxyl compound (polyol) and diisocyanates (crude MDI) [10] as shown in the chemical structure below:



Polyurethanes are block copolymers containing segments of low molecular weight polyester or polyether bonded to a urethane group (-NHCO-O) [11]. Generally, a polyether or polyester will produce soft segments, whereas MDI in the urethane bond will form hard segments. Polyurethane formation was carried out effectively through the control of carbon dioxide gas emissions in a polymerization system. Polyurethane is formed through the exothermic reaction between the compounds containing isocyanate (-NCO) and functional groups with active hydrogen (-XH).

4.1 Density

From the experiment, PU foam was classify as high-density rigid PU with density ranging from 196 kg/m^3 to 409 kg/m^3 as can be seen in Fig. 1. Normal density for industrial PU is 40-60 kg/m^3 depend on the application. Excess PKO-p increased the strength with the highest compressive strength at 11.4 MPa. The compression strength of the PU increased with increasing density but somehow affect the thermal conductivity of the lightweight concrete [5,12]. Therefore, in this study, 1:1 ratio of the PKO-p to MDI with a density of 206 kg/m^3 was set as the lightweight aggregate.

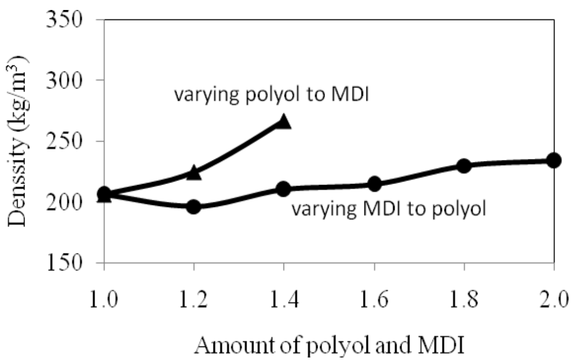


Fig. 1 The effects of varying PKO-p and MDI on the density of rigid PU

The effects of palm-based PU on the lightweight concrete density with three w/c ratios of the concrete mix as seen in Fig. 2. The investigated w/c ratios were 0.5, 0.6, and 0.7 with 0% to 5% (w/w) percentage loading of PU aggregate. Lower w/c ratio resulted in lower density sample, which consequently result in a dehydrated mixture and low workability. This resulted in density of approximately 1200 kg/m^3 to 1850 kg/m^3. On the other hand, increasing the amount of PU aggregate also dehydrated the mixtures and weakened the interaction between PU and the mortar. By increasing the volume of PU aggregate in the concrete from 1% to 5% (w/w), the density decreased within 22% to 35%.

To resolve the factors which influence the compressive strength and thermal conductivity, the w/c ratio is optimized to obtain a mixture with good workability [5,12,13]. At 0.6 w/c ratios and 3% (w/w) of PU is able to produce a homogeneous, highly workable, and easy-to cast lightweight concrete.

Needless to say that common practice applies 0.5 w/c ratio which is much depending on lightweight concrete manufacture. David et al. [7,14] stated that in terms of the water retained in the pores of the aggregate, most lightweight concretes retain, absorb, and release considerably more water than normal weight aggregates.

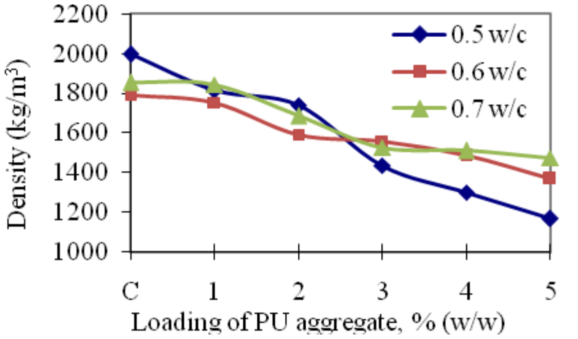


Fig. 2 The effects of palm-based PU addition on the lightweight concrete density with various w/c ratios of the concrete mix.

4.2 Compressive strength

Compressive strength for PU foam with varying PKO-p and crude MDI was shown in Fig. 3. The result by varying PKO-p attains 11.5 MPa significantly higher than varying crude MDI. The compression strength increased with the additional of PKO-p. Due to the dissimilar results, the control ratio (1:1) was selected as optimal lightweight aggregate. It was comparatively higher strength for lightweight aggregate [2].

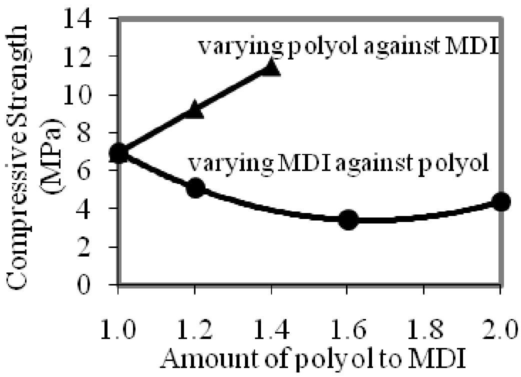


Fig. 3 The effect of PKO-p to MDI ratio on the compressive strength of rigid PU.

Meanwhile, the compressive strength of control and palm-based lightweight concrete can be seen in Fig. 4. At 7 and 28 days, the compressive strength of lightweight concrete with 3% PU increase from 11.3 MPa to 17.5 MPa. The graph indicates that compressive strength is a function of time. The strength increased upon prolongs exposure and gradually increased after 28 days to approximately 54%.

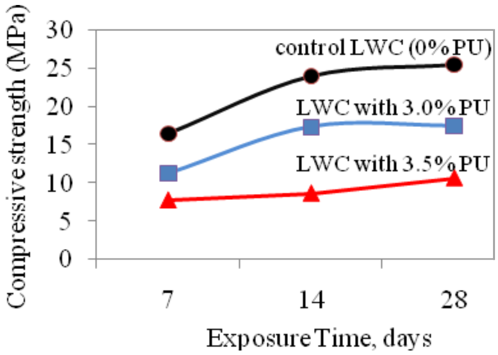


Fig. 4 Effect of varying PU addition in the lightweight concrete on the compressive strength

Apparently, the strength of this concrete is sufficient to utilize as structural concrete elements in accordance to the minimum strength requirement. ACI 213R-8 Guide for Structural Lightweight Aggregate Concrete defines structural lightweight aggregate concrete as those having a 28-day compressive strength of more than 17 MPa and air-dried weight not exceeding 1850 kg/m^3. After the compressive test, the cracks appeared on the concrete cubes. The length of the crack propagation dispersed to all direction. The failure mode of this concrete indicated that PU lightweight aggregate concrete experienced failure spread in all directions. It is categorized as a satisfactory failure following the standards. The stress transfer is prominently to all samples containing PU.

4.3 Distribution of aggregate and optical micrograph

By visual observation, PU without any special bonding agents or admixtures apparently showed an even distribution in the mortar and concrete matrix, as shown in Fig. 5. The broken fragment showed that cement paste occupied all voids and open pores of PU in contact zone. Meanwhile, PU also filled up–voids in the concrete system. In general, palm-based lightweight concrete showed good workability and could be easily compacted and turned to finished products.

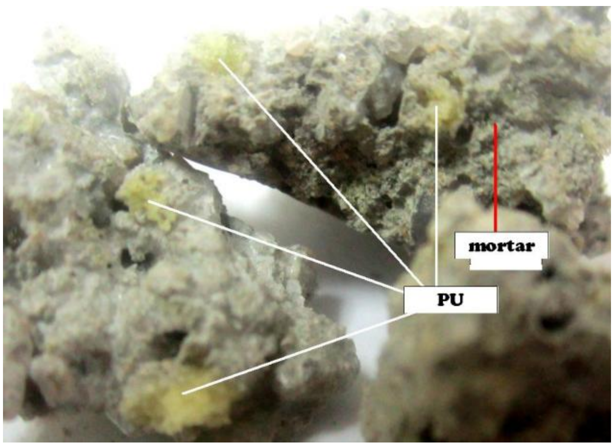


Fig. 5 Polyurethane (PU) covered by cement paste in the broken fragment of concrete.

The interfacial zones of palm-based lightweight concrete with PU was observed using optical microscope and presented in Fig. 6 below. Mechanical bonding completely interlocked PU and mortar. The well-built bonding between the PU aggregate and the mortar is attributable to the fact that the PU is not rounded in shape and has a rough surface. Jamkar et al. [15] stated that the mechanical bond between the aggregate surface and the cement paste, by virtue of interlocking, influences the strength of concrete.

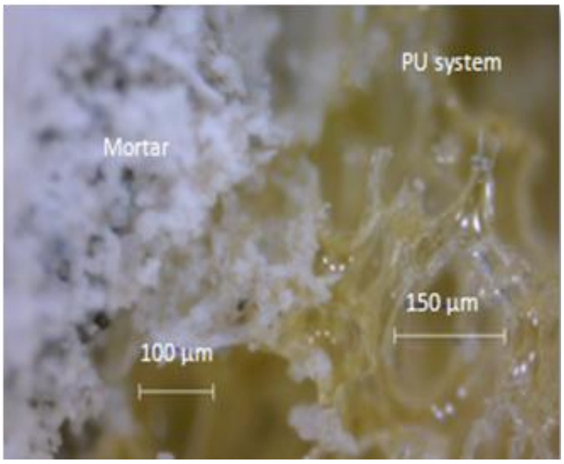


Fig. 6 Interfacial zones between concrete and PU observed using optical microscope at 500× magnifications.

5. Conclusion

The mix proportion of lightweight filled with palm-based polyurethane aggregate meets the requirement for structural concrete. The optimal PU ratio was 1:1 (PKO-p to MDI) and 1:2:0.6 (cement:sand:w/c) of concrete mix. By observations and the optical micrographs, the morphology of the PU in lightweight concrete indicated excellence interfacial transition zone. The mechanical bonding between the aggregate and the cement paste was completely interlocked to each other and the interfacial transition zone is generally stronger than the bulk paste. The strength of palm-based lightweight concrete increased with increasing strength and density of the lightweight aggregate. Further study will be cover on thermal properties and the application of lightweight concrete as building insulation materials.

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