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Characterisation of mechanical and thermal properties of epoxy grouts for composite repair of steel pipelines

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ABSTRACT

The mechanical and thermal properties of the grouts are critical to their potential application as infill materials in structural repair. In this paper, the mechanical and thermal behaviour of five epoxy based grouts were investigated to identify their prospects as a component of the composite repair for steel pipelines. The compressive strength and stiffness of the grouts are found to be 52–120 MPa and 1.7–11 GPa, respectively. The tensile, flexural and shear strengths of the grouts are found to be within the ranges of 11–32, 27–53, and 13–30 MPa, respectively. The tensile and flexural moduli range within 3–17, and 4–13 GPa, respectively. Thermal analysis of the grouts suggests that the glass transition temperature (T_g) within 60 and 90 °C which also provide the thermal applicability limits for the grouts in the composite repair of steel pipes. The development of compressive properties of three selected grouts over 28 days period was also investigated as well as the effect of the addition of coarse fillers.

1. Introduction

Fossil fuels like oil and gas provide the principal source of energy in the modern life [1]. At present, steel pipelines are the most preferable way to transport these natural resources from remote locations to our habitat premises. Steel pipes are often laid in-air, underground and underwater conditions in long distances or cross-country transportations. These pipes are carrying fluids and can go through adverse deterioration and susceptible to failure resulting from the chemical reactions and the mechanical forces. A wide range of rehabilitation techniques are available for onshore and offshore pipelines. Fibre-reinforced polymer (FRP) composites have been proven effective for repairing the metallic components and tubular pipes [2,3]. In general, there are two types of FRP repair systems for defective pipelines – flexible 'wet lay-up system' and pre-cured 'layered system' [4]. These repair systems use grout or 'putty' to fill the corroded or gouged section in the pipe and cylindrical sections [5]. Another development is a stand-off split sleeve that can be used to repair high pressure pipelines [6]. In this type of repair system, the annulus between the pipe and the outer sleeve is filled with suitable infill material to ensure a smooth bed for the composite layer. More importantly, the infill grout refills the damaged profile and provides a continuous support to minimise the outward distortion and transfer the load from pipe to the composite repair. Thus, the effectiveness of these repair systems largely depends on the performance of the grout.

Usually, cement grout with or without polymer modification and epoxy grouts are usually used as infill materials for repair and rehabilitation in construction industry. Epoxy grouts are recommended over cement grouts for application requiring high strength, rapid setting, dynamic load bearing, critical alignment, handling versatility and resistance against aggressive chemical environment [7,8]. Conventionally, the epoxy resins used in the rehabilitation works are the products of copolymerisation of Bisphenol A and epichlorohydrin [9]. Curing of most of the thermosetting polymers is affected when in contact with water in their uncured phase. By using special curing agents and methods, it is possible to produce systems which are insensitive to wet conditions and are capable of curing under water. This makes the epoxy grouts to have a wide range of application possibility than other grouts. The properties of grouts are significant parameters which are required in the numerical simulation or theoretical prediction of the behaviour of a repair system for an optimum design. Moreover, an evaluation of their thermal properties of the components of the repair is also important, as polymers exhibit degradation at elevated temperature. It is essential therefore to characterise the mechanical and thermal properties of epoxy grouts to determine their efficiency as infill materials in the repair.

In this paper, five commercially available grouts were selected based on their application and mechanical properties as reported

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Table 1
Composition of the grouts.

Grouts	Part-components	Mixing ratio	Primary constituents[i] (% weight)			
			Resin[h]	Hardener	Fine aggregate	Coarse aggregate
A	Resin with fine filler[a]: hardener	3.4:1.0[f]	22.75 (45.04)	11.46 (22.65)	65.79 (32.31)	–
B	Resin with fine filler[b]: hardener	3.4:1.0[f]	23.50 (46.92)	11.02 (21.47)	65.49 (31.60)	–
C	Resin with fine filler[c]: hardener	4.0:1.0[f]	27.37 (49.35)	9.52 (20.00)	63.11 (30.65)	–
D	Resin: hardener: coarse filler[d]	2.4:1.0:12.0[g]	15.58 (26.12)	6.49 (13.35)	77.92 (60.52)	
E	[(Resin with fine fillerc[c]: hardener): coarse fillere[e]]	[(4.0:1.0)[f]:1.0[g]]	13.66 (27.60)	4.76 (11.19)	31.55 (17.14)	50.03 (44.06)

[a] 0.06–350 μm.
[b] 0.05–90.0 μm.
[c] 0.05–300.0 μm.
[d] 45 μm – 2.36 mm.
[e] 45 μm – 2.36 mm.
[f] By volume.
[g] By weight.
[h] Bisphenol A and/or F epoxy resin.
[i] Values in the parenthesis are % volume.

by their respective manufacturers on their technical data sheets. These grouts were also selected as they have resistance against acids, bases and hydrocarbon based fluids, thus advantageous for underground and underwater pipeline repair. Thermal along with compressive, tensile, shear and flexural properties of these grouts were determined and their failure behaviour was observed to understand their performances in different loading conditions. The effect of addition of the fillers on the thermal properties was also determined. Finally, these properties were evaluated to determine their suitability as infill for composite repair for steel pipelines.

2. Details of investigation

2.1. Materials

Five epoxy grouts with different specified compositions of neat resin, hardener and aggregate were mixed using electric hand drill in a plastic bucket. The fifth grout was the modification of the third grout which was mixed with the equal weight of coarse filler. Table 1 shows the proportions of various ingredients of the grouts. Due to commercial confidentiality, the grouts were investigated in this article are named as Grout A, B, C, D, and E. Fig. 1 shows the ingredients of the grouts investigated in this study. The fillers used in the study are silica and calcium based inert fillers. Since the aim of this study was to characterise the behaviour of the mechanical properties, chemical analysis of the ingredients were not conducted.

2.2. Test programme

The test programme was divided into two stages. The first stage included the determination of the 7-day compressive, tensile, flexural, shear, and thermal properties of the grouts. Based on the results from the first stage, grouts C, D and E exhibited superior mechanical properties and the effect of curing period on the compressive properties of these grouts were investigated in the second stage. The test was carried out on the 25 mm diameter × 25 mm high cylindrical specimens for grouts C, D and E at 1, 3, 7, 14 and 28 days. In addition, the 50 mm diameter × 100 mm high cylindrical specimens were tested at 3, 7 and 14 days for grouts C and D to determine the size effects on compressive properties and failure patterns. Further, the 50 mm diameter compressive specimens of grout E were tested at 7 and 28 days.

2.3. Specimen preparation and test set up

2.3.1. Mechanical tests

Freshly mixed grouts were poured into the designated moulds. The specimens were removed from the moulds after 24 h, and cured in a controlled environment at 23 °C for 7 days prior to testing. The specimens were cut and polished to the required dimensions. Table 2 summarises the details of tests conducted on the prepared specimens. Relevant standards and practices are also shown in the table. All the mechanical characterisation tests other than the 50 mm diameter cylindrical compressive specimens were carried out using a 100 kN MTS hydraulic testing machine. Due to requirement of the higher capacity before yielding, the 50 mm diameter cylindrical compressive specimens were tested using a 2000 kN SANS servo-hydraulic compression testing machine. The compressive strain was measured from the crosshead displacement and initial height of the specimen. Fig. 2 shows mechanical testing of the prepared specimens. A laser extensometer was used to measure the strain data. The effective span length in-between the end supports for flexural test was 230 mm. V-notched shear specimens with a notched width of 12 mm at the middle were tested using Wyoming shear testing fixture.

2.3.2. Thermal analysis

Dynamic Mechanical Analysis (DMA) and Modulated Differential Scanning Calorimetry (MDSC) methods were used to determine the glass transition temperatures (T_g) of the grouts at 7 days. The dynamic mechanical analyser used to the carry out the dynamic test was a calibrated DMA Q800 with Universal Analysis 2000 V5.1 Build 92 manufactured by TA Instruments. Rectangular specimens with nominal dimensions of 60 mm long, 12 mm wide and 4 mm thick were prepared for the DMA analysis. The specimens were clamped in the three-point bending fixture of the DMA apparatus. The heating rate was 3 °C/min up to 180 °C. On the other hand, a calibrated DSC Q100 with Universal Analysis 2000 V8.1 Build 261 software manufactured by TA Instruments was used for the dynamic analysis. Dry nitrogen gas at 80 ml/min was used during the experiments to purge the DSC cell. Samples between 25 and 40 mg were enclosed in the standard DSC aluminium sample pans. Dynamic scans were performed at a heating rate of 10 °C/min from 35 to 150 °C.

3. Experimental results and discussion

3.1. Compressive properties

A summary of the test results of the tested grouts is given in Table 3. The lowest strength and stiffness are found for grout A. This is expected since grout A has the lowest resin content among grouts A, B and C. The yield and ultimate compressive strengths of grouts A are found to be 52 and 67 MPa, respectively. Also it can be seen from the table that grout E exhibited the highest compressive strength and stiffness among the investigated grouts de-