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Research Article

Comparison of Mechanical Properties of Epoxy Grouts for Pipeline Repair

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Abstract: Underground steel pipelines are the most efficient ways to transport oil and gas over a long distance. Steel pipes are considerably susceptible to deteriorate due to corrosion that can lead to serious pipeline failure. The application of fibre-reinforced composite overwrapped with epoxy grout on a damaged circular or rectangular structure is often practiced by the industry. The mechanical properties of the epoxy grouts are critical to their potential application as infill materials in pipeline repair. In this study, the mechanical behaviour of two epoxy based grouts was investigated. The mechanical tests were carried out accordance to the ASTM D695 for the compressive test, the ASTM D790 for the flexural test and the ASTM D638 for the tensile test. From the tests results, the compressive strength and stiffness of the grouts are found to be 60-88 MPa and 2.8-4.9 GPa, respectively. The flexural and tensile strengths of the grouts are found to be within the ranges of 35-43 MPa and 19-33 MPa, respectively. The flexural modulus was recorded at 3.91-11.87 GPa while tensile modulus range is within 2.07-4.65 GPa. From this study, it is concluded that the mechanical properties of the both grouts have the potential to be used in structural rehabilitation as suggested properties in previous research. In addition, for compressive strength, flexural strength and tensile strength less than 90, 45 and 35 MPa, both grouts can be considered as capable to serve its repair purpose in repair and rehabilitation.

Keywords: Epoxy grout, mechanical properties, pipelines, repair and rehabilitation

INTRODUCTION

Underground pipelines made from carbon steel are the most preferable way to transport these natural resources such as crude oil and gas from one point to another.Steel pipes that are laid underground can go through adverse deterioration and susceptible to failure due to the chemical reactions and the mechanical forces (Norhazilan *et al*., 2008; Zardasti *et al*., 2015). External corrosion has been identified as one of the two main causes of failure of buried pipelines worldwide (EGIG, 2008; CONCAWE, 2011; McConnell and Haswell, 2011; Norhazilan *et al*., 2012). Nowadays, a wide range of rehabilitation techniques and repair methods are available for onshore and offshore pipelines. There is arapid growth in the development and application of Fibre-Reinforced Polymer (FRP) composites, which are often used to reinforce corroded metallic pipelines. The use of fibre-reinforced polymer composites has been proven effective for repairing the metallic component and underground cylindrical elements (Mableson *et al*., 2000; Leong *et al*., 2001; Gibson, 2003; Cercone and Lockwood, 2005; Seica and Packer, 2007).

In structural repair of steel pipelines, the combination of composite layer and the infill grout is proposed by numerous researchers. In this type of repair system, the annulus between the pipe and the outer sleeve is filled with suitable grout or "putty" to fill the corroded or gouged section in the pipe and cylindrical sections (Duell *et al*., 2008). More importantly, the infill grout provides a continuous support to minimize the outward distortion and transfer the load from the pipe to the composite repair. The application of composite overwrap with epoxy grout on a damaged circular or rectangular structure is often practiced in repair industry (Ehsani, 2009). This type of repair methods prevents the defect failure through load transfer and restrains (Palmer-Jones and Paisley, 2000). Thus, the effectiveness of these repair systems largely depends on the performance of the grout (Shamsuddoha *et al*., 2013b).

The mechanical properties of the grout are one of the governing factors to determine the applicability and repair performance of the structure. Study done by Duell *et al*. (2008) used Diglycidyl Ether of Bisphenol-A (DGEBA) based epoxide cured with an alphatic amine hardener and a thixotropic fumed silica additive with compressive stress of about 33 MPa and compressive modulus 1.74 GPa to fill the defects on the steel pipe for restoring its undamaged dimensions. The results of their study showed that the failure was reached first in the fibre composite wrap indicating the

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success of filler to transfer load from steel to composites. A technical insight into an epoxy-grouted hot tap fittings technology for pipeline repair was described by Vu *et al*. (2011) where the compressive, tensile and flexural strengths specified in that article were 75, 23 and 50 MPa, respectively. In another study, Mattos *et al*. (2009) investigated an alternative repair system using two grout systems: silicon steel alloy filled polymers and oligomers and epoxy resins with aluminium powder. The compressive strengths of the abovementioned materials were 56 and 104 MPa while tensile strengths were 59 and 67 MPa, respectively.

The range of properties of epoxy grouts for structural application suggested by Mendis (1985). Table 1 shows relevant mechanical properties suggested for different range of repair and rehabilitation works. Grouts are susceptible to compressive, tensile, shear and flexural loading or a combination of these loadings based on their orientations and applications especially for epoxy grouts that are being used inside narrow confinements and in high performance applications. The properties of grouts are also the significant parameters that are required in the numerical simulation or theoretical prediction of the behaviour of a repair system for an optimum design. With the advancement of high performance composites, new challenges are emerging to find suitable epoxy grouts that can be used in combination with these materials to rehabilitate damaged structures. It is essential therefore to characterize the mechanical properties of available epoxy grouts to be able to determine their efficiency as infill materials in the repair.

In this study, the mechanical properties of two commercially available epoxy grouts that have high potential as infill components for pipeline repair were determined. The grouts were selected based on the properties listed by the manufacturer on their technical data sheets. These grouts were also claimed to have high resistance against acids, bases and hydrocarbon based fluids, thus advantageous for underground and underwater transportation facilities. The compressive, tensile and flexural properties of these grouts are determined and their failure behaviour is observed to understand their behaviour in different loading conditions.

MATERIALS AND METHODS

Two epoxy grouts with different specified compositions of neat resin, hardener and filler were selected. The properties of the selected commercial grouts are shown in Table 2.

Due to commercial confidentiality, the grouts were investigated in this study are named as 2-parts steel reinforced epoxy grout and 3-parts aggregate reinforced epoxy grout. The mixing procedures of the epoxy grout are described as follows. The proposed amount of resin and hardener for 2-parts steel reinforced grout were weighed based on ratio recommended in manufacturer's datasheet in clean and dry container. Then, the epoxy resin and hardener were thoroughly mixed. Similar to 3-parts aggregate reinforced epoxy grout, the resin and hardener were weighed according to mix proportions and mixed thoroughly. The aggregate was later added into the epoxy-hardener system and all the materials blended thoroughly to obtain a uniform mixture. Summary of the resin parts and mixing ratio are given in Table 3. Before casting, the molds made from the steel shall be applied with a special wax to ease the

Table 1: Typical properties of epoxy grout (Mendis, 1985)

Applications	Compressive strength (MPa)	Tensile strength (MPa)	Bond strength (MPa)
Bonding dissimilar materials	-	10-55	7-35
Concrete crack repair	41-97	14-55	14-35
Structural rehabilitation	83-97	28-48	28-41
Foundation and heavy machinery applications	≥97	-	15-28

Table 2: Grouts properties

Properties/Epoxy Grouts	3-Parts aggregate reinforced epoxy grout	2-Parts steel reinforced epoxy grout
Tensile Strength (N/mm^2)	~14	27.8
Tensile Modulus (N/mm^2)	N/A	9,360
Compressive Strength (N/mm^2)	~100	61.7
Compressive Modulus (N/mm^2)	~15,000	3,400
Flexural Strength (N/mm^2)	~20	56.4
Flexural Modulus (N/mm^2)	N/A	3,500
Lap Shear Strength (N/mm^2)	~34	9.6
Glass Transition Temperature (°C)	N/A	60

Table 3: Summary of grout components

Grouts	Part-components	Mixing ratio
2-Parts steel reinforced epoxy grout	Resin: Hardener	6.25 : 1 (by weight)
3-Parts aggregate reinforced epoxy grout	Resin: Hardener: Aggregates	2 : 1 : 12 (by weight)

Table 4: Tests, standards and dimensions

Tests	Compressive	Tensile	Flexure
Standards	ASTM: D695	ASTM: D638	ASTM:D790
Dimensions (mm)	12.7×12.7×50.8	13.0×3.2	127×12.7×3.2
Geometry	Prismatic	Dog bone	Prismatic
Loading rate (mm/min)	1.3	5.0	1.365

demolding work. All the samples were cured in room temperature for 24 h before tested.

The dimension of the mold and summaries of the details of tests conducted on the prepared specimens are given in Table 4. All the tests were carried out in accordance with the relevant standards using at least five specimens for each test. These tests were performed on a 25 kN universal testing machine (Instron) at room temperature. Since the aim of this study was to characterize the behaviour of the mechanical properties, chemical analysis of the ingredients was not conducted.

RESULTS AND DISCUSSION

Compressive properties: Table 5 shows a summary of the test results of the tested grouts. The ultimate strength of 2-parts steel reinforced epoxy grout is found to be 60.32 MPa. Also, it can be seen from the table that 3-parts aggregate reinforced epoxy grout exhibited the highest compressive strength and stiffness compared with the 2-parts steel reinforced epoxy grout. The ultimate strength and modulus of 3-parts aggregate reinforced epoxy grout are found to be 87.57 MPa and 4.87 GPa, respectively.

Typical compressive stress-strain behaviour of the tested grouts is shown in Fig. 1. The behaviour of the tested grouts is found to be different to each other. The maximum stress was observed at about 3% strain for these two grouts. The stress-strain behaviour of 3-parts aggregate epoxy grout was comparable to 2-parts steel reinforced epoxy grout exhibiting stiffer at initial part with maximum stress followed by a gradual decline of stress. As can be seen, 2-parts steel reinforced epoxy grout went through considerable bulging and show an elastic behaviour followed by a plastic deformation. From the plots, the strain at failure of both grouts is found to be about 5 and 8%. Chen *et al*. (2002) characterized the compressive stress-strain behaviour into five stages: linear elastic, non-linear elastic, yield-like behaviour, strain softening and nearly perfect plastic flow. The behaviour of 2-parts steel reinforced epoxy grout follows the first four stages in compressive stress-strain behaviour. The stress-strain relation of 3-parts aggregate epoxy grout is similar to the ideal behaviour shown by the fine filled epoxy resin where the stress descent down after maximum stresses (Chow, 1991).

Distinctive failure patterns were also observed in the grouts. The typical failure patterns of the samples are shown in Fig. 2 and 3 parts aggregate reinforced epoxy grout displayed combined brittle failure initiated with split inclined crack without any radial deformation prior to yield stress. On the other hand, the bulging was more noticeable in grouts of 2-parts steel reinforced epoxy grout.

Table 5: Summary of compressive properties

Grouts	Compressive Peak Strength (MPa)	Modulus (GPa)
2-parts steel reinforced epoxy grout	60.32±5.75	2.84±0.19
3-parts aggregate reinforced epoxy grout	87.57±1.98	4.87±0.37

Table 6: Summary of flexural properties

Grouts	Flexural Peak Strength (MPa)	Modulus (GPa)
2-parts steel reinforced epoxy grout	42.74±2.64	3.91±0.32
3-parts aggregate reinforced epoxy grout	34.57±2.40	11.87±0.62

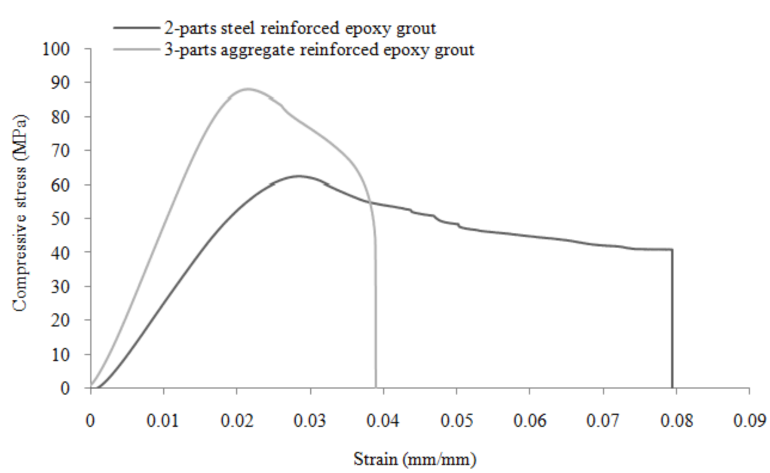

Fig. 1: Typical stress-strain behaviour of compressive samples

Fig. 2: Failure behaviours of compressive samples

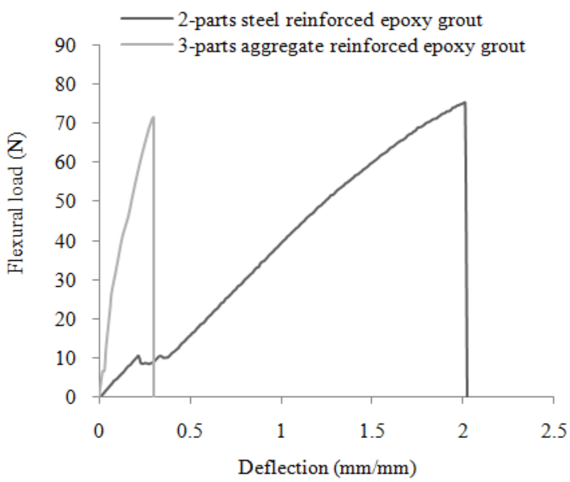

Fig. 3: Typical flexural load-deflection behaviour

(a) 2-Parts steel reinforced epoxy grout

(b) 3-Parts aggregate reinforced epoxy grout

Fig. 4: Typical failure of the flexural specimens

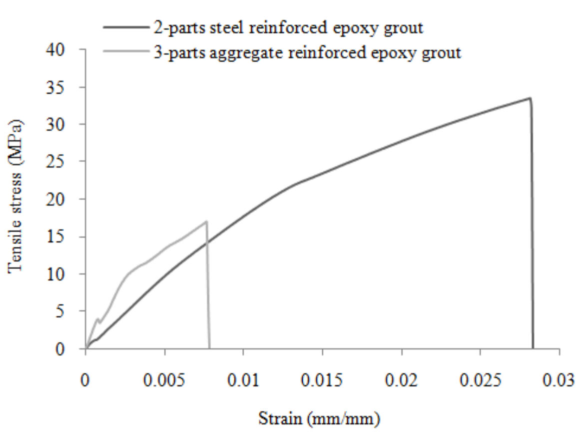

Fig. 5: Typical stress-strain behaviour of tensile samples

(a) 2-parts steel reinforced epoxy grout

(b) 3-parts aggregate reinforced epoxy grout

Fig. 6: Failure pattern of tensile specimens

Table 7: Summary of tensile properties

Grout	Tensile Peak strength (MPa)	 Modulus (GPa)
2-Parts steel reinforced epoxy grout	33.44±5.32	2.07±0.27
3-Parts aggregate reinforced epoxy grout	18.90 ± 4.62	4.65±0.53

Flexural properties: 2-parts steel reinforced epoxy grout has the highest flexural strength at 42.74 MPa and 3-parts aggregate reinforced epoxy grout exhibited the highest stiffness, 11.87 GPa as shown in Table 6. Figure 3 shows a typical comparison of load-displacement behaviour of flexural specimens. All the grouts show linear elastic load-deflection behaviour prior to failure. The load-deflection of 3-parts aggregate reinforced epoxy grout shows lower strength as well as lower deflection than 2-parts steel reinforced epoxy grout. This indicates brittleness of 3-parts grout due to inclusion of aggregate. The crack formations are almost vertical and perpendicular to the length of the specimen for both grouts. A typical comparison of the cracked specimens of the grouts is shown in Fig. 4.

Tensile properties: From the test results, it can be seen that the highest tensile strength was obtained in grout of 2-parts steel reinforced epoxy grout with a value of 33.44 MPa. Although the strength of 3-parts aggregate reinforced epoxy grout less than of 2-parts steel reinforced epoxy grout, higher tensile modulus is obtained in this grout with a value of about 4.65 GPa which are about two times higher than 2-parts steel reinforced epoxy grout. Hence, the aggregate filler has resulted in increment of stiffness in the 3-parts aggregate reinforced epoxy grout.

The comparison of typical stress-strain behaviours from each type of grout is shown in Fig. 5. All grouts showed linear elastic behaviour except for 2-parts steel reinforced epoxy grout which exhibits ductility before its failure. The 2-parts steel reinforced epoxy grout shows relatively prolonged ductile deformation under tensile load and exhibiting the highest strength, whereas 3-parts aggregate reinforced epoxy grout has failed at lower strain. The tensile failure of the grouts is comparable to each other with a split failure perpendicular to the length as shown in Fig. 6 and Table 7.

CONCLUSION

The mechanical properties of two commercially available epoxy grouts were investigated. The range of compressive, flexural and tensile strength were found to be 60-88 MPa, 35-43 MPa and 19-33 MPa, respectively. The ranges of compressive, flexural and tensile modulus were 2.8-4.9 GPa, 3.91-11.87 GPa and 2.07-4.65 GPa, respectively. According to the suggested properties by Mendis (1985), the both grouts have the potential to be used in structural rehabilitation. According to Thandavamoorthy *et al*. (2001), high performance grout with compressive strength 88 MPa is suitable to rehabilitate fatigue damaged tubular joints. The range of properties is suitable for structural and rehabilitation works. However, applicability of certain grout is dependent on property requirements in particular rehabilitation system and methods adopted. Thus, the mechanical behaviours of the grouts will aid to understanding their efficiency as infill materials in the repair.

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